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The development and use of aircraft evacuation modelling as a viable tool for the certification and safety analysis of passenger aircraft

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I want to thank everyone who has helped me to do this. My family, colleagues, sponsors and friends.

TABLE OF ABBREVIATIONS

NTSB	National Transport Safety Board
AAIB	Air Accident Investigatin Board
CAMI	Civil AeroMedical Institute
US	United States
UK	United Kingdom
CAA	Civil Aviation Authority
FAA	Federal Aviation Administration
JAA	Joint Aviation Authorities
VLTA	Very Large Transport Aircraft
BWB	Blended Wing Bodied
MB	Mega Wing Bodied
WB	Wide Bodied
NB	Narrow Bodied
DD	Double Deck
AASK	Air Accident Statistical Knowledge database
FED	Fractional Effective Dose
OBR	Out Board seat Removed
FSEG	Fire Safety Engineering Group
UoG	University of Greenwich

Exit designations used within AASK

FR	Forward Right
FL	Forward Left
MFL	Mid-Forward Left
MFR	Mid Forward Right
FLOW	Forward Left Over Wing
FROW	Forward Right Over Wing
OW	Over Wing
ROW	Right Over Wing
LOW	Left Over Wing
AROW	Aft Right Over Wing
ALOW	Aft Left Over Wing
MAL	Mid Aft Left
MAR	Mid Aft Right
AL	Aft Left
AR	Aft Right
TAIL	Tail exit

EXODUS terms and Statistics

PET	Personal Evacuation Time
CWT	Cummulative Wait Time
TET	Total Evacuation Time
OPS	Optimality Statistic
MNS	Mean Non-flow Statistic
TDIS	Total Dynamic Information Set
LOSIS	Line Of Sight Information Set
ACCM	Acitve Cabin Crew Management
TFT	Total Flow Time
EET	Exit Evacuation Time

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Abstract

Evacuation modelling technology offers designers and regulators of aircraft new opportunities to rigorously test designs and theories. However, before evacuation models can be used effectively they need to be understood by the regulatory and aviation industry, validated and developed further. This thesis tackles each of these aspects.

This thesis provides a detailed review of evacuation modelling with special emphasis on aviation evacuation models and the available data upon which models and understanding can be based. Of these the airEXODUS model is selected for this thesis and it is described in detail and critically evaluated. The evaluation revealed three main issues that needed to be addressed in order for aircraft evacuation modelling to advance. These issues relate to, (1) the limited quantity of model verification, (2) the inability of models to represent crew procedures, and (3) the limited behavioural capabilities of these models with regard to simulating real accidents as opposed to certification scenarios.

The fundamental accuracy and predictive capability of airEXODUS is evaluated. This is followed by a comprehensive investigation of cabin crew and passenger behaviour in 90-second certification trials and real emergency evacuations. The conclusions from this investigation serve as the basis for the development of new algorithms to addresses issues (2) and (3). Behavioural algorithms are developed to simulate cabin crew bypass in conjunction with algorithms for passengers exit choice and methods for simulated passengers to optimise their chosen route to an exit.

Finally, this thesis concludes by demonstrating the value of evacuation modelling in the design of future aircraft, the regulation of current aircraft and in understanding some of the contributing factors involved in past evacuation related disasters.

1 Introduction

Since its initiation the frequency of air travel has greatly increased. Indeed_in a recent US report to Congress [1] it was suggested that the number of emplanements each year will reach a billion (US) by the year 2010 (a 53% increase from today). Given this, it is then reassuring to know that aircraft accidents are rare occurrences. An air accident is defined as,

> *"an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage."[2]*

According to NTSB air accident statistics for the period 1982-2001, one accident occurs for every 400000 hours that an aircraft is flown. The term 'air accident', provided above, is however a broad category and covers accidents of varying severity. Indeed, according to the same NTSB report [3], most accidents are not serious (being defined as involving fire – pre-crash or postcrash, with at least one serious injury or fatality, and either substantial aircraft damage or complete destruction [3]). Indeed the NTSB found that for the period 1983-2000 only 26 from 568 (4.6%) of passenger flight accidents were classed as serious. In serious accidents they found that some 76.6%[3] of passengers survived, whilst 14.4% were killed during impact and a further 6.6% died from fires.

Given the relatively high survival rates it is apparent that in most serious accidents the performance of evacuation/rescue procedures and developments in fire/impact protection are factors in limiting the loss of life. Indeed, it is in the context of optimizing and understanding the evacuation of aircraft that the mathematical modelling of aircraft evacuation has been developed.

In this pursuit it is necessary to define and distinguish between the types of applications for which aircraft evacuation models can be used. The distinction between these application areas is made early in this thesis as it has an impact on the nature of the model used, and the quality and quantity of reliable data required to define the model and ultimately validate the model.

Currently there are two main areas of application for aircraft evacuation models. These relate to design/certification applications and the simulation of more realistic accident scenarios. While design and certification application areas should be considered as two separate areas, for all intents and purposes, the design requirement is predominately driven by the certification requirements.

In the aviation industry, aircraft regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In the USA the rules are known as the Federal Aviation Regulations (FAR) [4], while in Europe they are know as Joint Aviation Regulations (JAR) [5]. An example of one of the rules that has evolved over time relating to aircraft evacuation efficiency is the so-called "60-foot" rule. The rule appears in the FAR (i.e. 25.803 (f) (4)) [4], and there is an equivalent ruling in the JAR. The FAR rule states;

"For an airplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage, as measured parallel to the airplane's longitudinal axis between the nearest exit edges." [5]

These prescriptive regulations specify design rules that must be followed in the design of all commercial passenger aircraft carrying more than 44 passengers. Compliance with these rules can easily be visually checked by inspectors both during design – by viewing aircraft scale drawings - and when the first aircraft is produced. In addition to these prescriptive rules is a performance based requirement commonly known as the '90 second certification test' [12]. Compliance with this rule is demonstrated by performing a full-scale evacuation demonstration. The demonstration is performed with a representative cross-section of the travelling public (age and gender distribution), in darkness and utilizing only half of the exits normally available. Crew and passengers do not know before hand which exits will be available. The test involves evacuating all passengers and crew to the ground (using slides if they are fitted) within 90 seconds if the aircraft is to pass the performance test. A complete video record is made of the event including behaviour within the cabin and at the exits. The video recordings of the evacuations are a valuable source of data on the performance level achieved during these types of certification evacuations. The certification performance test is only intended to provide a measure of the performance of the aircraft under an artificial benchmark evacuation scenario. It is not intended to predict the performance of the aircraft under a realistic accident scenario. However, it allows the performance of different aircraft to be compared under a set of identical – if somewhat artificial – scenario conditions.

There are several difficulties with the current 90 second trial. There is considerable threat of injury to trial participants. Between 1972 and 1991 a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones [1]. In October 1991 during the McDonnell Douglas evacuation certification trial for the MD-11, a female volunteer sustained injuries leading to permanent paralysis. Another difficulty is the lack of realism inherent in the 90-second evacuation scenario. Volunteers are subject neither to trauma nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, the certification trial provides little useful information regarding the suitability of the cabin layout and design or the cabin crew procedures in the event of a real emergency. The Manchester disaster of 1985, in which 55 people lost their lives, serves as a tragic example. The last passenger to escape from the burning B737 aircraft emerged 5.5 minutes after the aircraft had ceased moving, while 15 years earlier in a UK certification trial, the entire load of passengers and crew evacuated the aircraft in 75 seconds [10,11]. In the certification trial, while passengers are keen to exit as quickly as possible, the behaviour exhibited is essentially co-operative, whereas in real accident situations the behaviour may become competitive. Even if complex issues of fire etc. are excluded from consideration, other relatively simple issues such as exit selection are far from realistic. In the standard certification test configuration typically all exits on one side of the aircraft are used. This practice bears little resemblance to realistic accident scenarios [6,7].

On a practical level, as only a single evacuation trial is necessary for certification requirements, there can be limited confidence that the test truly represents the evacuation capability of the aircraft. In addition, from a design point of view, a single test does not provide sufficient information to arrange the cabin layout for optimal evacuation efficiency, and does not even necessarily match the types of configuration flown by all the potential carriers.

Finally, each full-scale evacuation demonstration can be extremely expensive. For instance an evacuation trial for a wide-body aircraft costs in the vicinity of $US2 million [1]. While the cost may be small in comparison to development costs, it remains a sizeable expenditure.

A primary driver for the development of aircraft evacuation models is to augment or replace the current certification process. In this application the model is intended to simply replicate the 'live' certification trial and if possible to address the identified problems and shortcomings of the certification process. Looking beyond the role of models in satisfying the requirements of the 90-second certification trial, it is necessary for models to simulate 'actual' emergency scenarios. The modelling of real emergency evacuation is far more complex than certification modelling for a number of reasons. Firstly, intrinsic variability in real emergencies leads to a number of different possible evacuation scenarios. For example, whereas in one emergency evacuation the aircraft fuselage may expose the cabin interior to a life threatening fire [14], in another, the cabin may remain intact but passengers may be subjected to a mild threat of smoke [15]. The aircraft could be on its landing gear in one scenario [16] but may have partial failure in another [15]; the aircraft may be partially immersed in water as in the case of a runway overrun [17], etc. Thus the range of human behaviour that needs to be modelled is far more extensive than that exhibited by passengers in the 90-second certification scenario.

As an aside for readers that are unaware of aircraft cabin layout and terminology; an aircraft cabin is comprised of passenger seat belts arranged laterally in rows that are punctuated by longitudinal aisles. Aircraft regulations state that any seat must not be more than 3 rows away from an aisle measured laterally [4]. Thus in wide cabins - typically high capacity aircraft - it is necessary to have more than one longitundial passenger aisle (see Figure 1). On wide-bodied aircraft longitudinal aisles may be joined by lateral aisles; these are know as cross-aisles. Exits are placed in the cabin walls and may have escape slides. The area adjacent to the exit is known as the exit vestibule area. Exit vestibule areas are typically linked via cross-aisles. Interersted readers are referred to Appendix A for a more detailed description of aircraft cabin layouts and features.

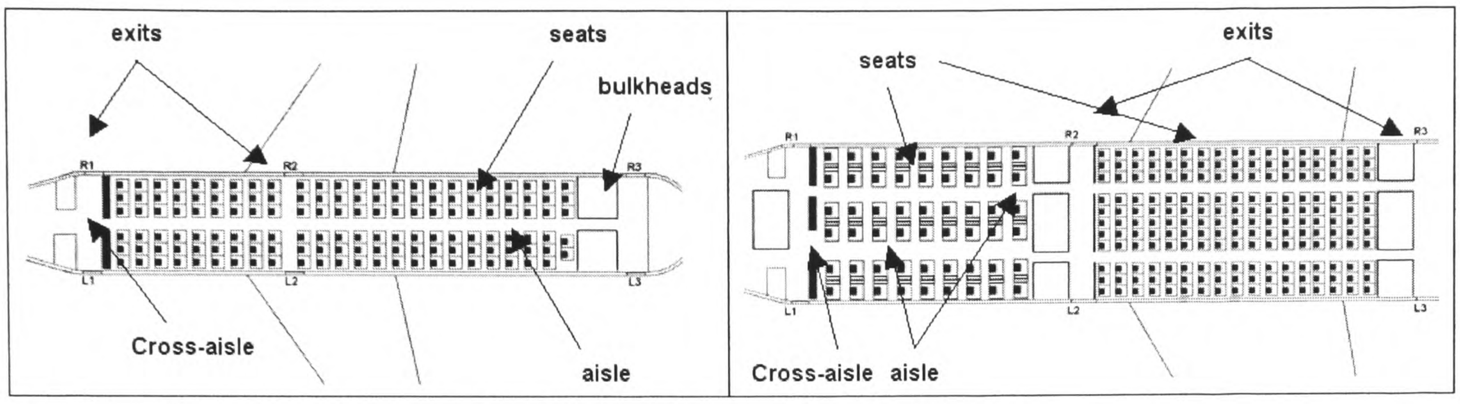


Figure 1: Hypothetical examples of a narrow-boided and wide-boided aircraft cabin

Returning to foucs of this work, this thesis examines the use of evacuation modelling to explore the issues described above, in order to answer many of the questions relating to the use of this technology and its suitability for this task. This work initially involves a critical review of the current evacuation models and the data that is available to them. This provides an overview of the field and the progress of current evacuation models to date. The review highlights potential models that are capable of being used for certification and accident analysis. From these the airEXODUS model is highlighted as the most developed model within the field and is therefore selected for detailed study in the remainder of this work. This is presented in Chapter 2 of the work.

Chapter 3 provides a summary of the current functionality of the airEXODUS model and highlights some areas requiring further development. This reveals two key questions that need to be answered in order for the model to be considered as a viable alternative for simulating the 90-second certification trials. Firstly, *"Can the results of a model be trusted, verified and interpretted?"* and secondly *"How can the results and behavioural capabilities of the model be improved?"* To answer this question three sub-questions are posed: *"What are the key behaviours that require extension?", "What data is currently available for the development of behaviour?"* and *"How can the data be used to quantify and understand the behaviours?"*

Looking beyond the current 90-second certification trial scenario towards the simulation of real emergency evacuations the third question asked in this thesis is *"Is the passenger behaviour model currently sophisticated enough to represent these types* *of behaviour exhibited by passengers in real accidents?"* Chapters 4-8 of this thesis systematically address each of these three questions.

Chapter 4 provides an answer to the first question (*"Can the results of a model be trusted, verified and interpretted?")*. In this chapter the capabilities of airEXODUS to simulate the current aircraft evacuation performance benchmark – the 90-seconds certification trial – is assessed. This involves subjecting the model to a battery of qualitative and quantitative tests. In order for the results of the evacuation model to be trusted it is crucial that they are comprehensively evaluated and as much as possible shown to be accurate. In Chapter 4 the performance of the model is assessed according to its underlying accuracy at *reproducing* the results of 90-second certification trails are examined and the model's capability when used to *predict* the results of 90-second certification trials. This analysis highlights the inability of the model to explicitly represent cabin crew procedures a failing which is addressed later in this work.

To answer questions 2 and 3 an original investigation of behaviour in 90-second certification trials and real emergency evacuations is performed in Chapter 5. A finding of this chapter is that that cabin management procedures are nearly always employed by cabin crew during certification trials [18, 19] and quite often during real emergency evacuation scenarios [14,20,15,21,22]. The investigation in Chapter 5 indicated that these procedures may involve crew instigated exit by-pass or in more severe emergency scenarios passengers' forming their own exit choice. **A finding of Chapter 5 was the possibility of conflicting goals between passengers and crew - crew are generally concerned with maximising exit utilisation and thereby reducing the overall evacuation time for the aircraft whereas passengers are generally concerned with attempting to reduce their personal (including persons with whom they are attached) evacuation times.** The investigation in Chapter 5, indicates that during certification evacuations, passengers are generally very compliant to crew instruction and are thus more likely to follow a crew command and to redirect to another exit than in real emergency scenarios especially those involving fire. In scenarios that involve fire passengers are more likely to be concerned with their own self interest.

Based on the findings of Chapter 5 this work suggests new models for crew-passenger interactions and develops algorithms to represent this behaviour within the airEXODUS evacuation model. Algorithms capable of simulating crew redirection procedures in 90-second certification trials are developed in Chapter 6. These are then extended to simulate behaviour in real emergency evacuations. This involves developing additional algorithms for passenger exit choice.

The investigation in Chapter 5 indicates that both passenger and crew decisions are based on the information that is obtained from the environment during the evacuation (referred to as dynamic information) and known aspects of their environment (referred to as static information). Mechanisms are provided within the models for passengers and crew to gather both types of information. Primarily this is achieved through a rudimentary implementation of sight and the restrictions that the geometry of the structure and the smoke conditions within the cabin impose upon passengers and crew. The resulting algorithms are more adaptive and allow passengers to look beyond their immediate surrounds and to appreciate the implications of the evolving evacuation dynamics within the cabin. This enables more realistic decisions to be made based on their available information. The algorithms developed in Chapter 6 are demonstrated using various certification and emergency evacuation scenarios.

Chapter 7 extends the behavioural capabilities further through the development of new algorithms based on the investigation of human behaviour presented in Chapter 5. Models to simulate passengers swapping to alternative aisles on wide-bodied and blended wing bodied (BWB) aircraft are developed. Again, the underlying behaviour is developed using a decision based approach in which passengers use dynamic information gathered from the visible environment. Models appropriate for 90-second applications and real emergency evacuations are developed.

Finally a new method of representing passenger seat climbing behaviour is developed. Prior to this thesis seat climbing behaviour within airEXODUS was reactive to local conditions only. Using the techniques developed in this work a more sophisticated representation is developed that enables passengers to make decisions based on information gathered from their visible environment. This uses some of the visibility functionality that is developed in Chapter 6.

The final chapter (Chapter 8) describes three studies that were performed using the methods developed in this thesis. The first undertakes a study of a current aviation regulation (the maximum exit separation FAR (i.e. 25.807 (f) (4)) [5]) using evacuation modelling techniques. The second study uses the model to examine evacuation issues for future aircraft design, such as the A380 or the proposed BWB aircraft. The model is used to provide an assessment of various evacuation scenarios. The final demonstrations, show how modelling can be used to understand human behaviour and predict the outcome of real emergency evacuations involving fire. The final chapter provides compelling evidence for the replacement of the current certification trial methodology with a more holistic approach.

This thesis represents an extension to the airEXODUS evacuation model. The model prior to the development in this thesis is describd in Chapter3 and should be taken as the starting point for this work. This work develops the model further, designing and coding new methods and new equations for simulating human behaviour in aircraft accidents. These models are based on empirical evidence from aircraft accidents and certification trials.

To summarise, evacuation modelling technology is potentially a valuable tool for aircraft designers and regulators to assess the evacuation efficiency of aircraft in a range of accident scenarios. This thesis undertakes an evaluation of evacuation models and their data and in doing so selects the airEXODUS evacuation model for detailed investigation. Three key limitations with the model are highlighted and then each systematically addressed. This leads to a model that is more capable of simulating both the 90-second certification requirement and real emergency evacuations. Finally, this thesis makes a compelling argument for wider use of evacuation modelling techniques in the design and regulation of passenger aircraft.

2 A Survey of Aircraft Evacuation Models and Related Data

2.1 *Introduction – The main types of* evacuation models

This chapter poses and answers the question *"Are there currently evacuation models appropriate for certification and accident applications. If so what are they, what are they lacking?"* To answer this question a review of evacuation modelling methods is presented with a particular focus on models that are designed to simulate evacuation from aircraft. This review describes the various methods available to simulate evacuation from any enclosure, be it a building or aircraft (see Section 2.2.1), the models that are currently available to simulate aircraft evacuation (see Section 2.2.3), the data requirements of these models and the sources of this data (see Section 2.4).

Recall that there are currently two main areas of application for aircraft evacuation models. These are for design/certification and for accident reconstruction. The distinction between the types of application that aircraft evacuation models can be used for has already been described in detail in Chapter 1 of this work. The distinction between these two areas is however highly important as it has an impact on the nature of the model used to service these different areas, and the quantity and quality of reliable data required in defining the model and used during its validation. Suffice to say that evacuation modelling for accident reconstruction is considerably more demanding than certification modelling. Despite this some models have been developed that to attempt to simulate real emergency evacuation scenarios and certification scenarios. This chapter examines all of the aircraft evacuation models that have been developed to date, including certification and accident simulation models.

Before continueing with the discussion it is useful to consider a typical aircraft evacuation. Summarising an aircraft evacuation is an extremely difficult task, as the dynamics would vary according to the type of scenario, i.e. destruction to the aircraft, presence of fire, passenger load, decisions of the crew, etc. That said it is considered useful at this stage to consider some of the features of an aircraft evacuation. An evacuation scenario is therefore described below for those readers unfamiliar with aircraft evacuation to give a flavour of an extremely well orchestrated evacuation scenario. Readers should be aware that in reality numerous additional behaviours and factors may occur that could influence the sequence of events described below, some of which are discussed throughout this thesis.

In an aircraft evacuation passengers would at some point be alerted to the requirement to evacuate, this may occur suddenly (i.e. an uncontained engine failure) or passenger may have had some time to prepare for the evacuation (i.e. an in-flight fire). In most aircraft evacuation scenarios there is little ambiguity in the call and need to evacuate the aircraft. That said in some accidents [17] and possibly in future in VLTA and BWB (e.g. super-jumbo or flying wing aircraft) some ambiguity may exist.

Operator procedures typically specify that to begin evacuation a clear evacuation instruction is transmitted by the flight crew over the Public Address (PA) system, e.g. "Evacuate, Left" for an evacuation via the left side exits. The flight crew may specify a portion of the aircraft exits that are to be used, i.e. Left or Right, in the event of a fire scenario. Subsequent to the evacuation instruction the crew should release their seat belts, stand, move to and check that their assigned exit is useable. Useable exits are those that will not subject users and/or cabin occupants to the threat of injury, fire and smoke ingress. Should they determine that evacuation is possible through their assigned exit they would open the exit and if present the escape slide would begin to deploy. If the crew determines that the exit is unusable they are required to guard the exit and direct passengers towards other useable exits onboard the aircraft. During this period passengers will have/be unbuckling their seat belts, standing, attempting to collect carry on luggage and evaluating their exit choices. Passengers seated next to small hatch exits are required to operate the exit hatch and may have begun doing so.

Once standing passengers typically begin to make their way towards the exits. In accident scenarios passengers typically choose their nearest useable exit [102,103] whereas in 90-second certification trials passengers are quickly directed by the crew towards exits that are optimal for the aircraft. During this period cabin crew at active and useable exits should be yelling and cagouling passengers. In making their way to the exit passengers would likely experience congestion. Likewise, whilst attempting to leave the seating rows and when moving through the aisle they would likely experience congestion.

Cabin crew at aircraft exits play an important part during the evacuation and are responsible for ushering passengers onto exit slides in as expeditious a manner as possible. In doing so they should command passengers to "jump not sit" and at exits with dual lane flows such as Type-A or Type B exits, to "form two lines". Assertive and effective cabin crew typically push passengers in the back to speed them on their way. Ineffective and non-assertive cabin crew simply command passengers without actually handling them. Dedicated Assist Spaces (DAS) are provided to reduce their obstruction of the exit whilst performing these duties.

Those cabin crew that are guarding inactive exits or cabin crew with free-roles to roam the cabin during the evacuation may start to redirect passengers between exits to speed the evacuation. Typically these events occur towards the middle/end of the evacuation. On wide-bodied aircraft passengers may elect to switch to empty aisles and in extreme evacuations passenger seat climbing behaviour has been reported. Seat climbing behaviour involves passengers climbing over seat backs rather than using the aisle. Once a cabin crew's area is cleared they may check the cabin visually and then evacuate via the exit slide.

Finally, whilst exit openings and slide deployments are required by aircraft regulations to fully deploy in seconds (typically 20 seconds), in practice the opening of a damaged exit has been known to take minutes. Likewise passengers have been known to take 45+ seconds to operate exit hatches. Similarly some passengers maybe able to operate their seat belt quickly whereas others may not.

2.2 Computer based evacuation models

The most significant developments in computer based evacuation modelling technology has occurred in the building industry. This has been the driving force for much of the development in evacuation modelling. This is somewhat ironic as one of the first computer based evacuation models to appear in the literature was an aircraft evacuation model, GPSS [23,24] in the 1970's. This model failed to convince engineers and regulatory authorities of the day, perhaps due to the limitations of the computers of the time or limitations in its modelling capabilities. As a result the area of aircraft evacuation modelling fell dormant for nearly 20 years.

In the interim, and completely independent of the earlier aircraft developments, the building industry saw the potential benefits in evacuation modelling and subsequently developed numerous models (EVACNET+ [53,54] and TAKAHASHI's MODEL [35], BGRAF [55], DONEGAN'S ENTROPY MODEL [56], EXITT [57,58], EGRESS [59,60], E-SCAPE [61], EVACSIM [62,63], EXIT89 [64,65], SIMULEX [66-68], MAGNETMODEL [27] PAXPORT [29-30], VEGAS [72,73], EXODUS [36-38,40-52], CRISP [74,75], WAYOUT [76]).

The development of these models was partially driven by the desire of architects to implement novel concepts in building designs that were beyond the scope of the regulatory framework. As these designs challenged the traditional bounds of size and space utilisation they also challenged the scope of the traditional prescriptive building regulations. Increasingly, engineers and regulatory officials were faced with dilemma of demonstrating in some manner that these new concepts in building design were safe (or at least offered equivalent levels of safety to previous buildings) and that the occupants would be able to efficiently evacuate in the event of an emergency.

Thus, in the building industry, research into quantifying and modelling human movement and behaviour has been underway for at least 30 years. This work has progressed down two routes, the first is concerned with the movement of people under normal non-emergency conditions. The second is concerned with the development of a capability to predict the movement of people under emergency conditions such as may result from the evacuation of a building subjected to a fire threat.

Some of the earliest work concerned with quantifying the movement of people under non-emergency conditions is that of Predtechenskii and Milinksii [25] and Fruin [26]. This research into movement capabilities of people in crowded areas and on stairs eventually lead to the development of movement models such as PEDROUTE/PAXPORT [29-30]. Evacuation research is somewhat more recent, one of the earliest published papers appeared in 1982 and concerns the modelling of emergency egress during fires [31].

In the following section of this document an attempt is made to describe the modelling methodologies available to simulate evacuation. This discussion is application independent and applies equally to building and aircraft evacuation models. Having established the principle methodologies available we go on to examine aviation evacuation models. A more detailed discussion of the modelling methodologies can be found in the work of Gwynne *et al* [33].

2.2.1 A review of the modelling methodologies used to simulate evacuation

Attempts to simulate evacuation essentially fall into two categories of model, those which only consider human movement and those which attempt to link movement with behaviour.

The first category of model concentrates solely on the carrying capacity of the structure and its various components. This type of model is often referred to as a "ball-bearing" model (also referred to as environmental determinism [34]) as individuals are treated as unthinking objects that automatically respond to external stimuli. In such a model, people are assumed to evacuate the structure, immediately ceasing any other activity. Furthermore, the direction and speed of egress is determined by physical considerations only (e.g. population densities, exit capacity, etc.). An extreme example of this type of model is one which ignores the population's individuality altogether and treats their egress en mass [35].

The second category of model takes into account not only the physical characteristics of the enclosure but treats the individual as an active agent taking into consideration his response to stimuli such as the various fire hazards and individual behaviour such as personal reaction times, exit preference etc.

A variety of different modelling methodologies are available by which to represent these different categories of evacuation model. Within the modelling methodologies adopted, there are also a number of ways in which to represent the enclosure, population and the behaviour of the population. The myriad approaches that are available led to the development of some 22 different building evacuation models and some 6 aircraft evacuation models. These models have been categorised [33] according to the underlying methodologies used to represent:

- Nature of model application,
- Enclosure representation,
- Population perspective, and
- Behavioural perspective.

2.2.1.1 Nature of model application

Broadly speaking, models that simulate evacuation tackle this problem in three fundamentally different manners: that of OPTIMISATION, SIMULATION, and RISK ASSESSMENT. The underlying principles associated with each of these approaches influences the models' capabilities.

Generally termed as optimisation models are models that assume occupants evacuate in as efficient a manner as possible, ignoring peripheral and non-evacuation activities. The evacuation paths taken are considered optima, as are the flow characteristics of people and exits. These tend to be models which cater for a large number of people or who treat the occupants as a homogenous ensemble, therefore not recognising individual behaviour. Simulation models attempt to represent the behaviour and movement observed in evacuations, not only to achieve accurate results, but to realistically represent the paths and decisions taken during an evacuation. Risk assessment models attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures, can be assessed.

Whichever approach is adopted, it is essential that the enclosure, geometry and population behaviour be represented. Each of these aspects can be modelled using one of several approaches.

2.2.1.2 Enclosure representation

The method that a model utilises in representing the enclosure is an important characteristic of a model, as it is a key determinant of the level of detail that the model can ultimately provide. Two methods are usually used to represent the enclosure: FINE and COARSE NETWORKS. In each case, space is descretised into sub-regions, and each sub-region is connected to its neighbours. The resolution of this subdivision distinguishes the two approaches.

Using the fine network approach space is subdivided into a series of nodes or tiles. Each node/tile represents an area of the space that may typically be occupied by one person. Connectivity between the nodes/tiles is represented via arcs, which the simulated people traverse when moving between spatial nodes/tiles. Thus, with a fine network model people move from location to location within compartments. The location of people within each compartment is exactly known. Large geometries generally comprise of thousands of nodes. Coordinate based systems are an extreme manifestation of the fine network paradigm in which the node size is reduced to very small sizes and people occupying many nodes at once.

In the coarse network approach space is subdivided into compartments or large logically consistent regions. In buildings these may represent rooms, stairwells, etc, whereas in aircraft they may represent aisles, seat rows, exit passageways, and so forth. The connectivity between these compartments is represented via arcs. People move between compartments via the connecting arcs. Knowledge of peoples' location within compartments is not exactly known, however it may be approximated via queuing algorithms. This approach presents difficulties when incorporating local movement and navigation including overtaking, the resolution of local conflicts, and obstacle avoidance. This is because the exact location of an individual is not represented, and therefore detailed calculations of individual movement and the interaction between individuals cannot be made. This limitation should be kept in mind when examining the behavioural models. The main benefit of this approach is that it reduces the amount of computer processing, memory and ultimately the simulation time that is required. However, this approximation is not necessary for small problem domains, such as aircraft cabins, given the large processing power of modern desktop computers.

2.2.1.3 Population perspective

Another important feature of evacuation models is the method they employ in representing people within the enclosure. This aspect of evacuation models is referred to as the population perspective. The population perspective of evacuation models are categorised as being either INDIVIDAUL or GLOBALLY based.

Models that have an INDIVIDUAL PERSPECTIVE represent each member of the population individually and track their progress throughout the simulation. Each member of the population can be assigned individual attributes, such as age, gender, movement rates, etc. Whilst these types of models treat each individual within the simulation as unique, they do not preclude the formation of groups.

Evacuation models that have a GLOBAL PERSPECTIVE do not recognise the individual, but delineate a population as a homogenous ensemble (or a grouping), without different identities. These models represent evacuation details not on the basis of which individual escaped, but on the numbers of occupants who escaped. This approach may be beneficial in both the management and the speed of the models, but lacks much of the detail available to the individual perspective. When employing a global perspective is impossible to model the effects of events on individual occupants (the effect of toxic fire gases, for instance). In this example, only a distributed or average - perhaps indicating the proportion of the population that had been effected - could be established throughout the population. This deficiency may not be considered serious in simple, homogenous populations, but in more realistic situations, it would seriously hinder an accurate understanding of the behaviour of the population.

2.2.1.4 Behavioural perspective

To represent the decision-making process employed by the occupants, the model must incorporate an appropriate method for determining occupant behaviour. The behavioural perspective adopted is influenced by the population and geometry approaches taken, and as such is the most complex of all the defining aspects. Using current modelling techniques there are five commonly used and sometimes mutually inclusive approaches to represent behaviour within evacuation models; FUNCTIONAL ANALOGY BEHAVIOUR, IMPLICIT BEHAVIOUR, RULE BASED BEHAVIOUR, ARTIFICIAL INTELLIGENCE based behaviour and NO BEHAVIOURAL COMPONENT.

FUNCTIONAL ANALOGY MODELS apply an equation, or set of equations, derived from a non-evacuation related discipline (e.g. the functions which drive a Magnetic based model were taken from Physics), to the entire population, which then completely governs the population's response. All the individuals will be affected in the same way by this function and therefore will react in a deterministic manner to its influences, und

Some evacuation models have NO BEHAVIOURAL RULES at all. These models simply simulate the physical movement of the people. Peoples' decisions are formed on the basis of physical influences, rather than through simulating more complex human decision processes.

IMPLICIT MODELS do not represent the behaviour explicitly but make use of secondary data to represent their affects. These types of models are highly dependant upon the availability, reliability and validity of the data used.

Models which explicitly recognise the behavioural traits of individual occupants, usually make use of a RULE BASED system. These models have a set of rules, or heuristics, that govern the behaviour of simulated people within the model. These rules can be triggered in specific circumstances, and in such circumstances, have an effect. A problem with this style of decision-making process is that in simplistic methods the same decisions are taken under the same circumstances, in a deterministic fashion. In such instances the possible natural variations in outcomes through repetitions are not modelled. Most of the rule based models overcome this problem by introducing a stochastic component to the decision making process. This topic is discussed in more detail later (see Section 2.4).

ARTIFICIAL INTELLIGENCE based models utilise methods from artificial intelligence to mimic human intelligence in simulated people. Whilst this approach can yield realistic behaviour the level of user control is somewhat reduced.

2.2.2 Building and Aircraft evacuation models

As already mentioned, evacuation modelling for the built environment is more highly developed than evacuation modelling in the aviation industry. As a result there are many more models available for simulating evacuation from the built environment than from aviation environments. It should be noted at this stage that building evacuation models cannot easily and reliably be used for aviation applications. This is due in part to the unique behaviour exhibited by passengers and crew in aircraft evacuations and key structural features that differentiate aircraft from buildings. For example, behaviours, such as seat jumping, and cabin crew re-direction and structural features such as exits with slides make it difficult to simply apply a building evacuation model to an aircraft evacuation situation. Occasionally, building models have been used to simulate the evacuation of aircraft [59]. Not surprisingly the model predictions were poor. It is for these reasons that specialised aircraft evacuation models have been developed.

2.2.3 A review of aircraft evacuation models

Over the past 30 years only seven aviation evacuation models have been reported in the open literature. In chronological order they are:

1970 to 1980	General Purpose Simulation System (GPSS) developed by the FAA,
1987 to 1992	Gourary Associates (GA) model developed by Gourary Associates,
1990 to 1994	AIREVAC/ARCEVAC developed by Aviation Research Corporation
1994 to 1996	Macey's Risk Assessment Model developed by Cranfield University
1996 to 1996	The Oklahoma Object Orientated (OOO) model
1989 to now	EXODUS developed by the Fire Safety Engineering Group of the University of Greenwich
2001 to now	Robbin's Discrete Element Method (DEM) developed by Department of Mathematics at The University of Strathclyde

Of these, it appears that development of three models, namely, GPSS [23,24], GA [70] and ARCEVAC [69] has now been abandoned, whilst the OOO [79] model was a theoretical framework, never actually implemented. An earlier review of aircraft evacuation models was undertaken by Jeff Marcus of CAMI (Civil Aero-Medical Institute) in 1994 [80]. The review presented here brings this earlier review up to date.

2.2.3.1 General Features

As mentioned in Section 2.2.1.1, models have previously been categorised as being developed for use as either risk assessment, optimisation and/or simulation tools [33]. All of the aircraft evacuation models to date have been SIMULATION models (a possible exception is the MACEY [77] model). While the model as a whole is a risk assessment model, it relies on an simulation model to determine evacuation. We will therefore consider this component of the MACEY model to be a simulation evacuation model.

In Section 2.1 it was also stated that there are essentially two types of aviation application, the simulation of the 90 second trial and the simulation of real accident scenarios. Three aircraft evacuation models have been developed primarily to simulate REAL EMERGENCY evacuations (ARCEVAC [69] and GOURARY [70]), one model has been developed to simulate 90-SECOND certification evacuations (GPSS [23,24]) and three models have been developed specifically to simulate both 90 second certification trials and real emergency evacuations (EXODUS [36-38,40-52], MACEY [77] and DEM [71]).

If the model is intended to simulate real accident scenarios it will need the capability to represent fire scenarios. This can be accomplished through the incorporation of a hazard sub-model. The hazard sub-model is intended to represent the spatial and temporal distribution of fire hazards such as smoke, heat and toxic gases. The method of representing fire hazards is in some part dependent upon the nature of the enclosure representation. Models that utilise a coarse network approach to represent space will be forced to simplify the representation of fire hazards. In such cases, the hazard distribution would be represented as a uniform distribution within the defined spatial zone. Models utilising a fine spatial network to represent space can also represent the hazards as a uniform distribution over a predefined region of space (or zone) (e.g. GOURARY [70] and ARCEVAC [69]) or elect to represent a unique hazard value at each node/tile location within the geometry (e.g. EXODUS [36-38,40-52] and MACEY [77]). Models such as EXODUS can utilise either approach.

Determining hazard values to use in such calculations is discussed in Section 2.4.3.3. It is sufficient now to know that they can be obtained either via fire test experiments [81,82] and/or rough estimates, or via computer based fire simulation models such as Zone models [83,] or Computational Fire Dynamics (CFD) [87] models

Models that represent fire hazards should also have a representation of its affects on the simulated passengers. Human exposure to a thermo-toxic hazard would affect passenger's behaviour and their physiology. The behaviour model employed determines the behavioural response. However; a toxicity model is required to represent the passengers' physiological response.

To some extent the approach used to represent the population determines the maximum sophistication of the toxicity model that can be employed. Models that have an individual population perspective could simulate the response of each unique individual to fire hazard exposure, with each individual having unique tolerance limits.

A model with a simplistic representation of toxicity (e.g. GOURARY [70]), typically assigns passengers with an arbitrary endurance or stamina attribute that represents the individuals threshold to thermo-toxic exposure. The attribute is decreased by cumulative exposure until either incapacitation and/or expiry occurs. Unfortunately, the arbitrary nature of this attribute makes reliable predictions of human response to fire hazards difficult.

By contrast some models (e.g. EXODUS [36-38,40-52] and MACEY [77]) make use of complex fractional effective dose models (i.e. FED models) to predict the physiological response of passengers to fire hazard exposure (see Section 2.4.3.3). Incapacitation/expiry is determined via an empirically determined cumulative fractional effect that is determined according to actual exposure during the simulation.

Other models may completely ignore the thermo-toxic affects of real emergency environments (e.g. ARCEVAC [69] and DEM [71]). However, its presence may affect the behaviour of passengers (ARCEVAC [69]).

Another major feature of aviation evacuation models is their ability to represent the interaction of passengers with cabin crew where actions of cabin crew are highly influential on the evolving dynamics of the aircraft evacuation. For instance, cabin crewmembers prepare exits for use, redirect passengers and assist passengers at exits. These actions must be represented within the aircraft evacuation model in some way. Methods of representing cabin crew within aircraft evacuation models are categorised as being IMPLICIT, EXPLICIT, USER DRIVEN or NONE.

Some models completely ignore cabin crewmembers (e.g. MACEY [77]). Thus cabin crewmember tasks, such as exit preparation, is performed by passengers. Models with an IMPLICIT representation of cabin crew (e.g. GPSS [23,24] and DEM [71]), do not physically represent cabin crew within the simulation, although their actions are represented. For example, the affect of having an implicit assertive cabin crewmember adjacent to an exit may lead to a faster exit hesitations distribution being utilised. Likewise, crew could be represented through the assignment of relatively low times for exit preparation.

Models that have an EXPLICIT representation of cabin crew (e.g. ARCEVAC [69]), physically model the cabin crew as an individual within the simulation. The model determines events, such as the length of time required to prepare exits for use. Using exit preparation time as an example, the model would move the crewmember to the exit then the crewmember would open the exit and deploy the escape slide. Other actions such as crew redirection can also be represented explicitly. Some models are capable of both IMPLICIT and EXPLICIT representation of cabin crew (e.g. EXODUS [36-38,40-52]).

Finally, some models require user intervention in order to simulate the redirection of passengers (e.g. GOURARY [70]). These types of models require the user to monitor the unfolding evacuation and determine from the model output when redirection is required.

A key feature of aircraft evacuation models, and one that distinguishes them from building models, is the need to represent the behaviour of passengers when using aviation specific components, such as exit dimensions, shapes or escape slides. Some models use empirical data (GPSS [23,24] and EXODUS [36-38,40-52]) to specify realistic delays appropriate to the aircraft components, i.e. Type-I, Type-III exits etc. Such data is derived from analysis of experimental studies and 90-second certification trials. Through the use of this empirical data these models predict realistic flow rates through the exit. Some models (GOURARY [70], ARCEVAC [69], MACEY [77] and DEM [71] models) use a probability of exiting as a function of exit size and cabin crewmember proximity (GOURARY [70]), other models tend to assume an arbitrary cap on exit capability such as only allowing one passenger to occupy an escape slide at any one time (DEM [71]). Essentially, these approaches impose a flow rate upon the exit. The models parameters are then altered until something approaching the desired flow rates is generated.

2.2.3.2 FAA GPSS model

The FAA model was developed in the 1970's and was intended to simulate 90-second certification scenarios. The model was designed to run on the massive mainframe computers of the day. The software was written using IBM's General Purpose Simulation System (GPSS) language.

Aircraft geometries were created within the GPSS programming language. The model did not have a user interface but was operated via the programming language itself. Alternative geometries and populations were created via reprogramming the model to represent the desired aircraft geometry.

Space within the model was represented using a coarse network interconnected with arcs. Thus, the aircraft was divided into components such as aisles, exit passageways, seat blocks, etc. GPSS identified the individual location of each of the passengers, so theoretically each passenger could be tracked throughout the simulation. However, passenger model parameters were assigned uniform values within the model, as the authors could not empirically define individual parameters and their likely affects.

The behaviour of passengers within the model was rule based. There were, for example specific rules that allowed passengers to redirect to shorter exit queues as well as rules governing the movement of passengers between aircraft components, such as seats and aisles. An assumption used in their redirection algorithm was that the passenger reached the alternative exit queue before a gap in the flow emerged. In addition to the behavioural rules, the model made use of

	FORWARD EXIT			OVERWING EXIT			AFT EXIT			TOTAL TIME
RUN	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILIZATION	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILIZATION	NUMBER OF PASSENGERS	TIME FOR LAST PERSON OUT	AVERAGE UTILIZATION	FOR ALL PASSENGERS OUT
1	38	82.2	.592	48	101.2	.922	38	69.2	.484	101.2
2	40	85.8	.663	46	86.9	.921	38	70.8	.561	85.9
3	39	81.2	.576	47	100.3	.922	38	71.9	.476	100.3
4	37	87.1	.650	49	97.8	.953	38	71.1	.637	97.8
5	41	83.3	.712	45	83.6	.910	38	73.0	.628	83.6
6	40	81.2	.754	46	82.9	.910	38	47.2	.534	82.9
7	38	83.2	.661	48	89.8	.924	38	73.4	.602	89.8
8	40	82.6	.719	46	78.1	.863	38	69.5	.582	82.6
9	44	88.9	.760	42	74.2	.783	38	65.6	.593	88.9
10	44	87.5	.730	43	73.7	.811	38	70.2	.606	87.5
11	45	93.8	.795	41	73.4	.757	36	67.8	.500	93.8
12	44	85.8	.730	42	76.8	.745	38	72.7	.581	85.8
13	38	73.2	.603	48	90.0	.974	38	75.1	.614	90.0
14	39	79.1	.565	47	90.3	.924	38	70.8	.585	90.3
15	39	80.3	.730	47	87.8	.755	38	70.6	.636	80.3
16	42	92.2	.764	44	78.2	.742	38	71.8	.529	92.2
17	42	97.3	.753	44	84.6	.795	38	70.6	.524	93.3
18	41	89.1	.730	45	73.5	.793	38	70.6	.553	89.1
19	35	78.8	.593	51	82.3	.917	38	68.8	.593	83.3
20	45	95.7	.755	42	72.8	.700	36	69.5	.482	95.7
$\bar{X}$	40.5	86.84	.6876	45.5	85.90	.8485	38.0	70.47	.5537	89.63
S	2.7	6.15	.0678	2.7	9.70	.0538	0.0	2.24	.0527	6.38

Figure 2: An example of the results from the GPSS model [23,24]

empirically determined data in generating a random delay as passengers passed through an exit. The exit probability delay functions were calculated using data from CAMI (see Section 2.4.3.1) for various different exit types. A further assumption of the model was that only three passengers could occupy each lane of an escape slide at any one time. A Type-A escape slide could therefore have a maximum passenger load of six passengers. Finally, exit preparation times were assigned to individual exits. These were also determined from previous experimental trials at CAMI. A consequence of the exit delay probabilities was that the model was stochastic.

No hazard or toxicity model was required as the GPSS model was designed only to simulate 90-second certification trial evacuations. The model output was numerical. As output, the model calculated the times that passengers hesitated at the exits, the gap between passenger arrivals at the exit and the time spent on the slide for four gender/age groups. In addition the total evacuation time for the aircraft and the time of the last person out, continuous and non-continuous flow rates for each exit were output. An example of the results of the GPSS model output can be seen in Figure 2.

The GPSS model was validated using the four-certification trial cases shown in Table 1. It can be seen that the average total evacuation time of the model was only within 10% of the certification trial in one of the cases (L-1011 with redirection). The disparity in the remaining cases was attributed to variability in the performance of passengers and crew during the 90-second certification trial. It was thus concluded that more data was required from experimental trials in order to better represent motivation levels during emergency evacuations.

Table 1: GPSS validation history (reproduced from [80])

Type of Aircraft	Passenger Load	Certification Time (sec)	Average Simulated Time (sec)	Redirection
B747	527	66.2	84.0	Yes
L1011	356	101.1	93.5	No
L1011	356	82.0	54.9	Yes
L1011	411	89.7	79.6	Yes

2.2.3.3 The GA Model

Gourary Associates (GA) of the USA developed a model through part FAA and commercial funding during the late 1980's and early 1990's. The primary intention of the GA model was to simulate realistic emergency scenarios rather than the 90-second certification scenario. The GA model used a fine network method of representing space allowing one or more passengers to occupy each spatial node/tile. The population was represented as a collection of individual passengers, who were assigned individual attributes such as, Endurance, Agility, Sex, Age and Wakeup time, i.e. response time. The progress of each passenger was tracked throughout the evacuation.

The model was limited to 38 seat rows with up to six passengers within each seat row. The model allowed six exits. These exits could be positioned anywhere in the geometry. The model had a graphical user interface and ran in near real time. Edited geometries could be saved for later use.

Movement speeds were not empirically determined and attributed to each passenger as a parameter. Instead, each passenger had a probability of moving to an adjacent cell, based on the cells occupancy level, i.e. empty, occupied or full, the proximity of cabin crew and the type of cell being traversed. For example, the probability of a passenger moving between cells was higher in aisle nodes than in seat cells. Thus, different passenger speeds were modelled for specific terrain. In addition to this, the occupancy level of the targeted cell affected the probability of movement. For example, there was a higher probability of movement to unoccupied cells rather than those that were already occupied by a person. If a cell was full, i.e. containing two active people, then the probability of movement was impossible, i.e. zero.

Expired passengers were counted as occupying cells. This could lead to the model "jamming". An algorithm was included that enabled passengers to "bypass" cells that were occupied by expired passengers.

The probabilistic movement approach was also applied to passenger exiting. Once a passenger reached the exit they had a probability of exiting the aircraft. More effective exits would be modelled via increased probabilities. The proximity of cabin crewmember(s) at the exit increased the probability of exiting still further. Given the probabilistic nature of the movement sub-model, the GA model would have to be considered as stochastic in nature.

This model contained little further passenger behaviour from that already discussed. Indeed, the only notable other behaviour within the GA model, was passenger redirection.

Prior to running the model each passenger was assigned an exit. However, they could be diverted to other exits during the evacuation. Within GA this was accomplished without using computerised rules, but through user intervention via the keyboard whilst the simulation run. Firstly the user had to select an exit using the function keys F1-F6. This had the effect of placing a cabin crewmember at the exit. Having placed the crewmember at an exit the user pressed the arrow keys to divert passengers to the nearest exit in the selected direction. The drawback with this approach was that only one cabin crewmember could be modelled at any one time. A potential solution to this was provided via the ability to redirect every passenger in the simulation. This was accomplished by pressing <CONTROL+D> during the simulation.

Since GA was intended to simulate real emergency evacuations, hazard and toxicity models were required. Indeed, GA had a rudimentary representation of fire hazards and toxicity. GA had an environmental hostility value which decreased passengers endurance attribute until it had fully expired, at which point they died. The model allowed for two different hazard zones, with each having its own severity. However, the distribution of hazards throughout the aircraft cabin and their affect on passengers was completely arbitrary.

Indeed, the main failing of the GA model was that the parameters that it required were not empirically determined [80]. The user was required to manually set all model parameters, such as exiting probability, passenger endurance and the toxicity of the environment. The arbitrary parameters would then be highly influential on the outcome of any simulations. In addition, whilst it is stated in its literature that validation was performed, its results were not published [70, 80].

2.2.3.4 AIREVAC/ARCEVAC

In the late 1980's the South West Research Institute (SWRI) through Air Transport Association (ATA) funding began developing a model called AIREVAC. Later, in the early 1990's AIREVAC, became known as ARCEVAC and its development was taken over by Aviation Research Corporation of Canada as a commercial venture.

The ARCEVAC model was designed to simulate real emergency evacuation scenarios. ARCEVAC employed a fine network spatial representation, with space being descretised according to a user specific grid size. With a suitable small grid size the model functioned as a coordinate based scheme. As such passengers were assigned cross-sectional widths to represent the girth of their bodies.

Without rewriting the code, the model was limited to simulating the evacuations from the B727. At the time, the model ran considerably slower than real time. ARCEVAC had a user-friendly graphical user interface (see Figure 3) to allow the model to be configured. Simulation and geometry files could be saved for later use. The model was capable of outputting charts and data on the performance of the aircraft as a whole or individual exits (see Figure 4).

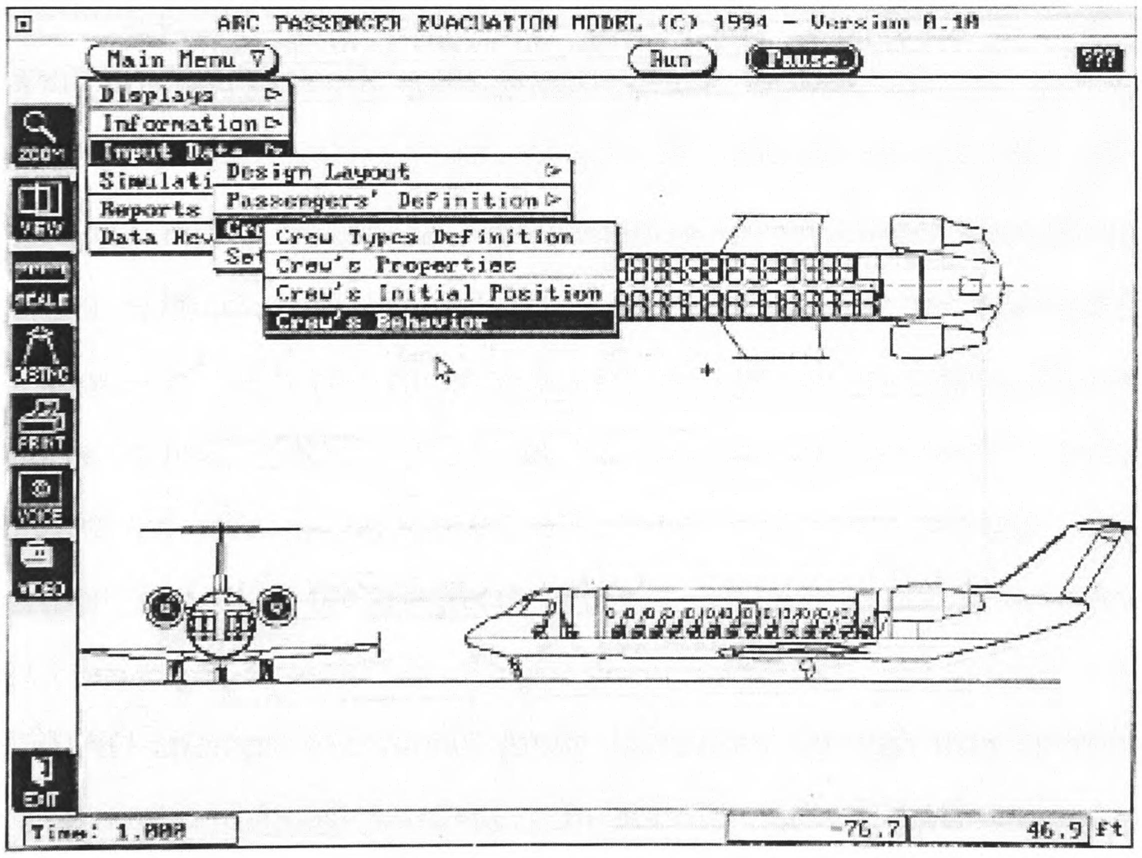


Figure 3: Graphic of screen output from the ARCEVAC model

The population perspective of this model was individually based, tracking each individual passenger throughout the evacuation. Indeed, passengers and crew within ARCEVAC contained numerous individual parameters, such as Sex, Age, Constitution, Weight, Height, Cross Sectional Area, Agility, Selfishness and Group Selfishness. Not only were passengers attributed with individual physical attributes, but they also have physiological and social attributes such as state-of-mind and selfishness.

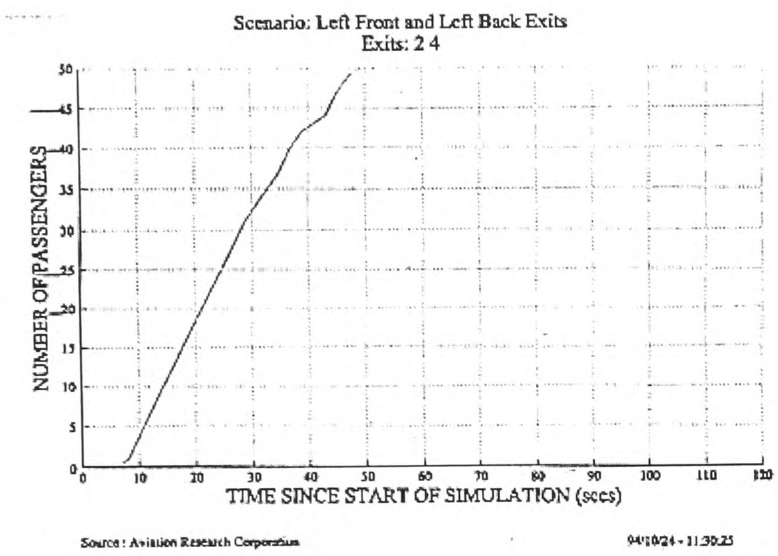


Figure 4: Example output from the ARCEVAC model

To assist in defining populations within the model a randomiser was provided. The randomiser generated populations according to specified minimum and maximum values for different groups. Within these groups and for the purposes of representing group bonding, peoples' relationship with each other could be specified as being either, business colleagues, friends or family members.

ARCEVAC had a rule-base representation of passenger behaviour. The defining passenger parameters were used in conjunction with the behaviour rules to determine the response of each passenger to specific events during the evacuation. Indeed the behaviour within ARCEVAC was fairly sophisticated for its time. ARCEVAC contained the fundamental rules governing movement between nodes and exiting behaviour. Details of these aspects were not available in published literature.

ARCEVAC attempted to model group behaviour through user specified relationships and a group selfishness attribute. In addition ARCEVAC attempted to model the psychological state of mind of passengers during their evacuation. A numerical *state-of-mind* attribute represented the following states: *calm, alert, nervous, panicky* and *shock.* The state-of-mind modified both passenger movement and their response to specific stimuli.

Within the model, *Calm* passengers followed normal crew behaviour and were capable of changing directions to other exits without crossing seating. *Alert* passengers would choose the best evacuation route and were able to cross seating. *Alert* crewmembers gained a *performance* level. *Nervous* passengers would choose the best exit but would not redirect from their chosen exit without crew intervention. They were able to cross seating. *Nervous* crew would drop two levels of *performance. Panicky* passengers would choose any path to any exit so long as a threat is not present. They would not redirect themselves. *Panicky* crew would attempt to evacuate themselves. *Shocked* passengers would move randomly around the cabin space.

ARCEVAC had extensive capabilities with respect to simulating the actions of cabin crew. Cabin crew were modelled explicitly and are assigned specific “missions”. Missions ranged from searching seats, stairs or aisles for immobilised passengers, to rescue/aid and general evacuation management. Assigning the mission of searching seats, stairs and aisles would make the cabin crewmember search these aircraft components for immobilised passengers. The aid mission would initiate an attempt at rescuing these passengers. The assist in evacuation mission would allow the cabin crewmember to redirect passengers to alternative exits or to assist in the flow of passengers through exits or monuments. Benefit to passengers from cabin crewmember missions was derived from a calmer state of mind attribute, increased agility attribute and more efficient exit choice.

Combinations of missions could be specified in order of priority. For example, the cabin crewmembers main priority could be to improve the flow rate of passengers through exits with the secondary mission of helping immobilised passengers.

Specific attributes, such as valour and performance, were assigned to cabin crew and influenced their ability to perform their tasks. The valour attribute was used in determining the point at which the cabin crewmember would abandon their mission in favour of their own survival. The performance level of the cabin crewmembers was specified through a series of probabilities and attribute modifiers. For example, the crewmembers’ ability at assisting passengers during evacuation was determined via an agility modifier attribute. Probabilities were specified to represent the assertiveness of cabin crewmembers in issuing commands and the subservience of passengers to them.

The final performance attribute was the check interval. This was used to represents the speed that the cabin crewmembers could perform their tasks, i.e. the frequency of their actions.

Since ARCEVAC was designed to simulate real emergency evacuations hazard and toxicity models were required. Whilst ARCEVAC contained a grid-based hazard model, it did not contain a toxicity model. Consequently the presence of hazards only affected the behaviour of passengers, for example increasing the passengers' state-of-mind attributes, rather than leading to incapacitation through thermo-toxic exposure. For example, explosions and or smoke would increase the state-of-mind of the passengers and crewmembers, i.e. it may move from being Alert to Nervous.

Like GA, ARCEVAC suffers from the arbitrary nature of its model parameters. This deficiency was even more acute given the vast number of parameters that were used in the model. In short, the model contained too many arbitrary parameters. Indeed, even the qualitative nature of most of the physiological variables are open to dispute.

ARCEVAC was validated against the evacuation of a Canadair Regional B727 Jet that underwent certification in 1993. The result of ARCEVAC was an evacuation time under 60 seconds. Due to its proprietary nature the results of the certification trial were not made public. However, during the validation exercise ARCEVAC generated graphs showing the number of passengers out as a function of time for individual exits as well as the aircraft as a whole. The validation exercise also considered different combinations of exit choice whilst maintaining an exit from each exit pair.

2.2.3.5 airEXODUS

The EXODUS software is developed by the University of Greenwich (UoG) Fire Safety Engineering Group (FSEG). EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. Development on EXODUS began in 1989. EXODUS was originally designed for use with aircraft, however, its modular format makes it ideally suited for adaptation to other types of environment. As a result its range of application has grown, as has the number of specific EXODUS products. The family of models consists of buildingEXODUS [37-40,50-52], maritimeEXODUS [41,42] and airEXODUS [36,44-49] for the built environment, marine/off-shore industries and aviation applications respectively. airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

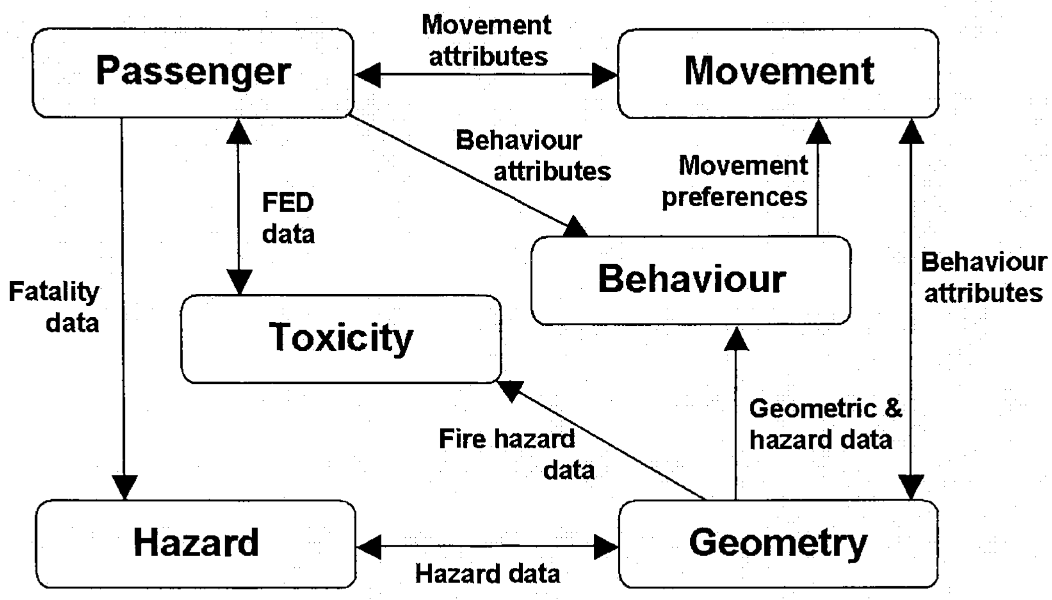


Figure 5: airEXODUS Submodel Interaction

EXODUS comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models (see Figure 5). The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The spatial grid maps out the geometry of the structure, locating exits, internal compartments, obstacles, etc (see Figure 6). Geometries can involve multiple decks, connected by staircases. The structure layout can be specified using either a DXF file produced by a CAD package, or the interactive tools provided. The grid is made up of nodes and arcs with each node representing a small region of space and each arc representing the distance between each node. Individuals travel from node to node along the arcs.

The Population Sub-model allows the nature of the passenger population to be specified. The population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the structural layout of their environment, response times etc. airEXODUS assigns passengers with over 20 defining attributes, such as Gender, Age, Weight, Height, Agility, Drive, six different movement speeds (for different types of motion and terrain), Response Times, Patience and Social Genes.

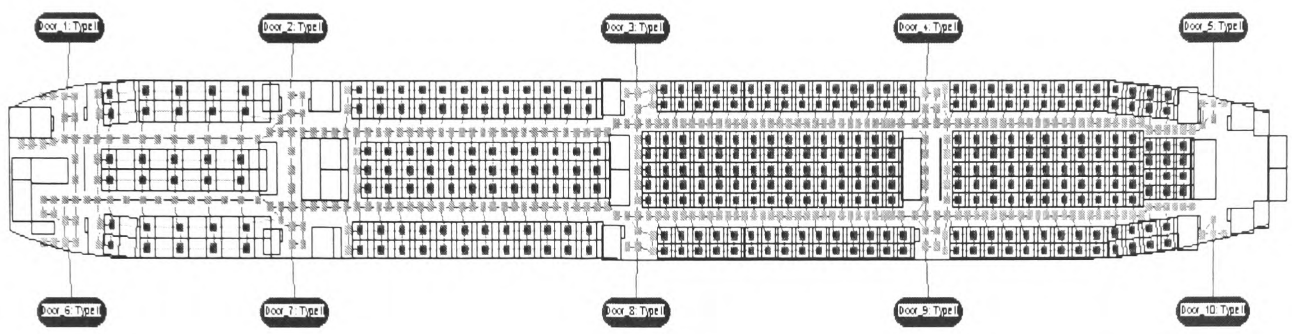


Figure 6: Cabin layout in airEXODUS. View depicted represents the interactive graphics component within airEXODUS. Aircraft depicted has five pairs of exits. The node structure showing seats, aisles and cross-aisles is clearly depicted.

On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model. The Behaviour Sub-model functions on two levels. These levels are known as Global and Local behaviour. Global behaviour involves implementing an escape strategy that may lead an occupant to exit via their nearest serviceable exit or most familiar exit. The desired global behaviour is set by the user, but may be modified or overridden through the dictates of local behaviour, which includes such considerations as determining the occupants initial response, conflict resolution, overtaking and the selection of possible detouring routes. In addition a number of localised decision-making processes are available to each individual according to the conditions in which they find themselves and the information available to them. This includes the ability to customise their egress route according to the levels of congestion around them, the environmental conditions and the social relationships within the population. Social relationships, group behaviour and hierarchical structures are modelled through the use of a 'gene' concept [52], where group members are identified through the sharing of social "genes". Passengers are able to adapt their evacuation strategy according to a rational use of the information available to them, i.e. they may wish to communicate information to other passengers, identified as a group member.

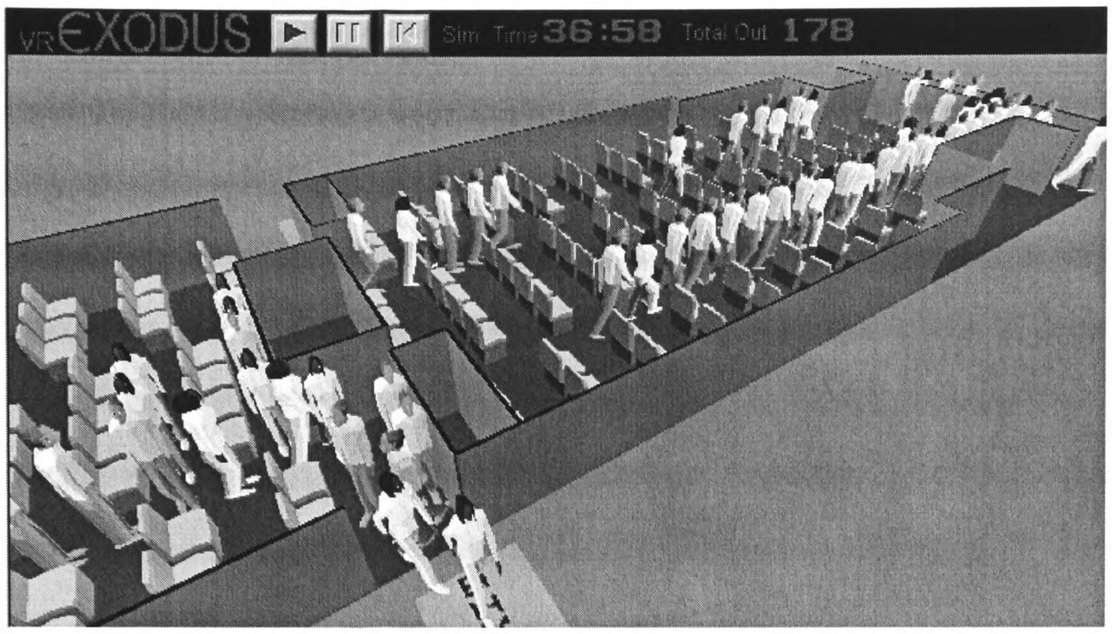


Figure 7: vrEXODUS generated scene from an airEXODUS evacuation simulation

The Toxicity submodel determines the physiological impact of the environment upon the occupant. To determine the effect of the fire hazards on occupants, airEXODUS uses a Fractional Effective Dose (FED) toxicity model [88,89] (see 2.4.3.3 for more details). This model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. In addition to this behaviour, the passengers are able to respond to the environmental conditions by adjusting their behaviour. The thermal and toxic environment is determined by the Hazard submodel. airEXODUS does not predict these hazards but can accept experimental data or numerical data from other models including a direct software link to the CFAST fire zone model [84,85]. airEXODUS produces a range of outputs, both graphical and textual. Interactive two-dimensional animated graphics are generated as the software is running that allows the user to observe the evacuation as it takes place. The graphics are interactive allowing the user to interrogate occupants and events. In addition, a data output file is produced containing all the relevant information generated by the simulation, including a copy of the input data. To aid in the interpretation of results, a post-processor virtual-reality graphics environment known as vrEXODUS has been developed, providing an animated three-dimensional representation of the evacuation (see Figure 7).

airEXODUS makes use of 90-second certification data [90] to specify certain model parameters. One of the most important parameters for representing aircraft style exits is the Passenger Exit Delay Time. This time represents two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit.

In general, the exit hesitation time is due in main to passengers either waiting at the exit for the path to clear and/or contemplating how to negotiate the exit. In either case, the exit negotiation stage does not usually start until there is space for it to commence. Furthermore, the process of passing through the exit and travelling from the exit to the ground are considered as separate events that can occur in parallel.

Within airEXODUS the exit delay time distribution is segmented into subintervals described by uniform distributions. The technique is dependent on the user having a good representation of the actual delay time distribution. In the current version of the software this data is extracted from past certification trials [90,91]. For example, consider main deck Type-A exits with assertive cabin crew. Data from 11 previous certification tests involving Type-A exits with assertive cabin crew was available. The data was derived from the following aircraft: A310 (255 passenger), A310 (280 passenger), B747, B747-300, B747-SR, B767-300, B767-346, B777-200 (420 passenger), B777-200 (440 passenger), DC10 and MD11 [90,91]. In total, passenger exit delay time data from 20 exits representing some 2078 passengers is used to define the passenger exit delay time distribution.

airEXODUS and the EXODUS software in general has undergone a significant amount of validation. airEXODUS has been used to simulate evacuation trials conducted at Cranfield University in their B737 cabin simulator [45,92]. In addition, a more challenging validation exercise was requested by the UK CAA, requiring airEXODUS to predict the performance of a modified Boeing B767 aircraft, (designated the B767-304ER), prior to the actual test, in order to establish the predictive capabilities of airEXODUS for 90 second certification trials. A confidential report [93] containing details of the model formulation and results of the simulations was produced by FSEG and distributed to the UK CAA and US FAA prior to the trial, and Boeing after the trial. A description of some of the results of the airEXODUS predictions may be found published literature [45].

2.2.3.6 DEM

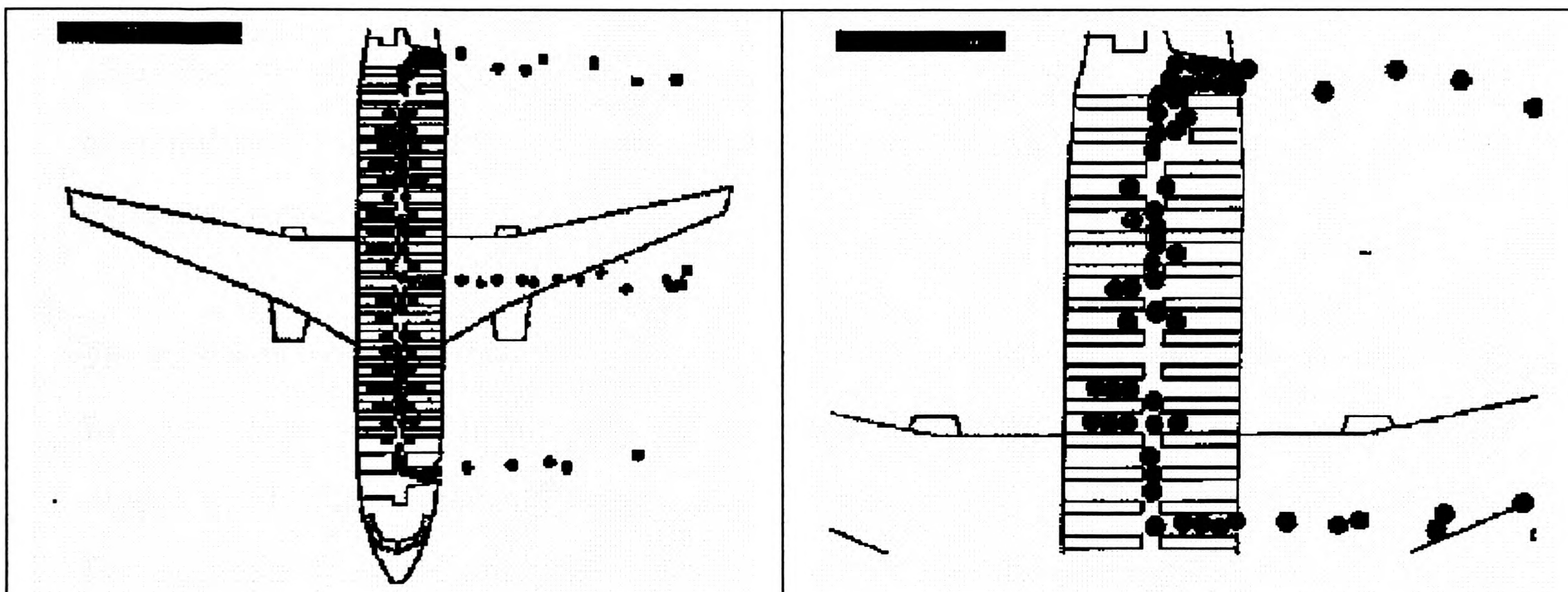
The DEM (Discrete Element Method) model was developed in the UK by the University of Strathclyde in 2000 [71]. The model is intended to simulate 90-second certification style evacuations and real emergency evacuations. The model has a graphical user interface that shows the position of each passenger during the simulation. The model has been demonstrated using the B737-300 aircraft (see Figure 8), although presumably other models could be specified.

The model uses a coordinate based fine network spatial representation and tracks the movement of each passenger during their evacuation. Additionally, each passenger has limited defining attributes, such as *dominance*, *movement speed* and *size*. Thus, the population perspective of this model is individual based.

The movement model employed by DEM is a functional analogy based on differential equations that govern the motion of Newtonian soft sphere grains. A consequence of this approach is that the passenger shape is circular. In addition, physical forces such as friction, torque and inertia are all variables within the Newtonian laws of motion and are thus model parameters. Another by-product of the functional analogy is that collisions between passengers result in them temporarily contracting and if the collision is side-on, then some amount of spin is imparted that causes passengers to rotate. Motion towards exits is achieved via artificial external forces that pull the soft sphere grains towards exits. The artificial attractive force that is exerted by the exits can be targeted at specific soft sphere grains within the model, thus different passengers can be made to use different exits. All of these parameters – which are a by-product of the functional analogy approach – have not in themselves been proven to be analogous to human behaviour.

There is no mention of exit preparation delays or passenger response times within published literature for this model [71]. Exit flow rates are governed by the supply to the exits and a rule imposed by the model designers that only one passenger may occupy an escape slide at any one time. An additional delay was specified to represent that incurred by passengers negotiating Type-III exits. The delay was represented by the imposition of a uniform 2-second delay to passengers at the exit. Indeed, this delay exemplifies a major failing of this model. Namely, that the model parameter spe ary.

Whilst, the movement model is a functional analogy, some movement rules exist in order to avoid blockages and to simulate passenger redirection. The dominance attribute is used to avoid blockages in contested areas such as aisles. The DEM model does not represent cabin crewmembers either explicitly or implicitly. However, passengers may redirect themselves to alternative exits if the *"queue is half the length of the queue that they are already in"* [71]. In addition, at the date of writing, none of the published literature relating to this model indicates that there is a representation of either hazards or their thermo-toxic effects.



(a) (b)

Figure 8: Screen shot from the DEM model

The model was validated against the evacuation of the B737-300. As the model is deterministic, only one result was generated (81 seconds) which the authors stated compares well with 75 seconds achieved during the 90-second certification trial. As a further example of the model, the B737-300 DEM model exit availability was configured as in the Manchester air crash [10]. The resultant evacuation time of 117 seconds was 44% higher than the certification case. The model did not attempt to simulate the affects of fire or the delays in preparing the over wing exit for use that occurred in the actual accident. These validation cases are rather meaningless when the completely arbitrary nature of the model parameters is considered. Any agreement with actual results should be considered fortuitous rather than by design.

2.2.3.7 Macey's model

During the 1990's as part of a PhD thesis, Macey et al developed a risk assessment model at Cranfield University. The model was intended to analyse real and certification evacuations.

The model was designed for risk assessment purposes and was intended to simulate the total set of evacuation scenarios. To facilitate this, the probabilities of specific scenarios occurring were determined from a comprehensive analysis of over 200 previous airliner accidents. Event trees were formulated from this analysis specifically for use within the risk assessment model. Probabilities such as the likelihood of the scenario involving impact, cabin burn through, internal and/or external fires were determined. In accidents involving fuselage breaks, a probability distribution of the break location was also determined. Additional probabilistic data was supplied regarding the likely cabin layout, weather conditions, phase of flight, airport distance, availability of emergency services, impact effects, fuselage split, fuel spills, jammed exits and impact injuries.

The risk assessment model comprised of fire, toxicity and evacuation sub-models. The fire scenarios were "empirically" determined from the supplied probabilities. The model would then randomly choose a scenario according to the supplied probabilities. For example, from the analysis of past accidents it was determined that 90% of the fire scenarios involved burn-through and external fire scenarios. Thus, it is quite likely that the model would choose to simulate a fire scenario that involved either burn-through and/or an external fire. Whilst recognising the need for an internal model of fires they were not represented within the risk assessment model. The likely location of the fire was determined from probabilities derived from analysis of 72 past accidents.

Having selected a scenario it was then modelled in 2-dimensions. The consequence of the 2-dimensional fire model is that common effects such as smoke/gas layering or stratification were not represented. The height of the fire was taken as being head height, i.e. 1.5 metres from the floor. The fire growth, smoke and toxic gases were modelled using differential equations. These simplifications are considered a significant weakness of the model as they cannot accurately represent fire development which is inherently three-dimensional.

A 2-dimensional airflow sub-model was used to simulate the spread of fire and smoke taking into account the scenario and aircraft configuration, i.e. the presence of fuselage ruptures and combinations of open exits. The thermo-toxic affects of the fire were modelled using 'standard' FED models.

The evacuation sub-model was a fine network model with a graphical user interface capable of outputting the evacuation (see Figure 9). In total 80 different aircraft layouts were supplied with the model. It was stated that these include *"all major passenger aircraft types currently in service"*. Additional layouts could be generated using a syntax driven specification tool.

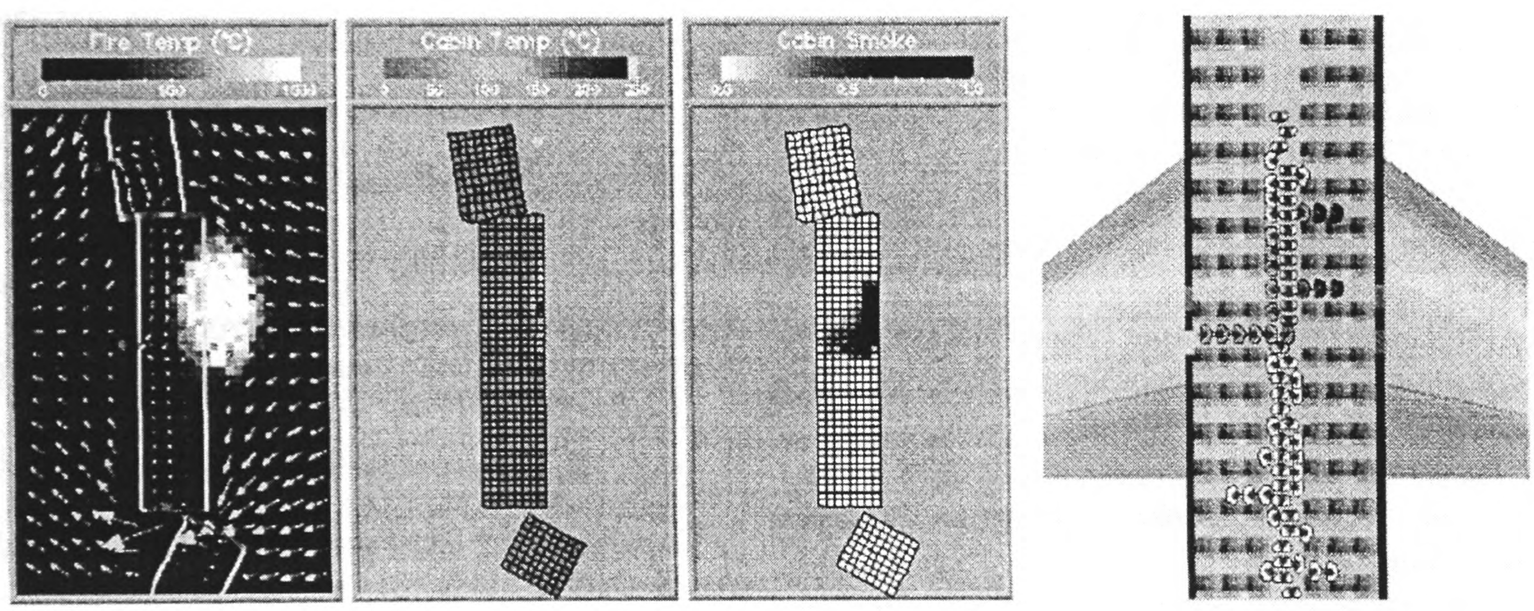


Figure 9: Screen shot of the output from Macey's model. Left is the airflow model, centre is the thermo-toxic model, and right is the evacuation model

It was recommended that the cell size within the model was set to 0.15 by 0.2m. Since passengers' dimensions are often larger than this, it was necessary for passengers to occupy more than one cell. Within the model each passenger could be tracked throughout the entire evacuation. In addition the passengers had "expandable" individual attributes such as reaction time, movement speed, narcosis and irritant levels. The population perspective was therefore individually based.

The behavioural basis of this model was rule driven. The basic passenger behaviour was that they moved towards their nearest exit. The nearest exits could however; become less attractive should there be a large number of users or the exit inactive.

Passengers were able to switch exits to adjacent active exits should their queues become smaller.

The published literature did not state that empirical data was used to determine the delay that passengers experienced in traversing exits. Instead exits were calibrated so that they generated flow rates that were equivalent to those generated during 90-second certification trials. Exit flow rates were not an output for the model but were imposed. It was recognised that these flow rates were not appropriate to real emergency scenarios in which cabin conditions and passenger motivation is very different.

Since cabin sections could rupture it may also have been necessary to supply data on the length of time required for passengers to traverse the ruptures. However, no data was supplied. Finally, a crash severity attribute was specified as part of the scenario definition. The crash severity value was used to degrade passenger movement rates through specific sections of the cabin.

This model had neither an explicit nor implicit representation of cabin crewmembers. Indeed they were not modelled at all. A consequence of this was that passengers were required to open the aircraft's exits.

The fire and toxicity sub-models were linked to the evacuation model so that individual thermo-toxic affects could be calculated for every passenger in the evacuation.

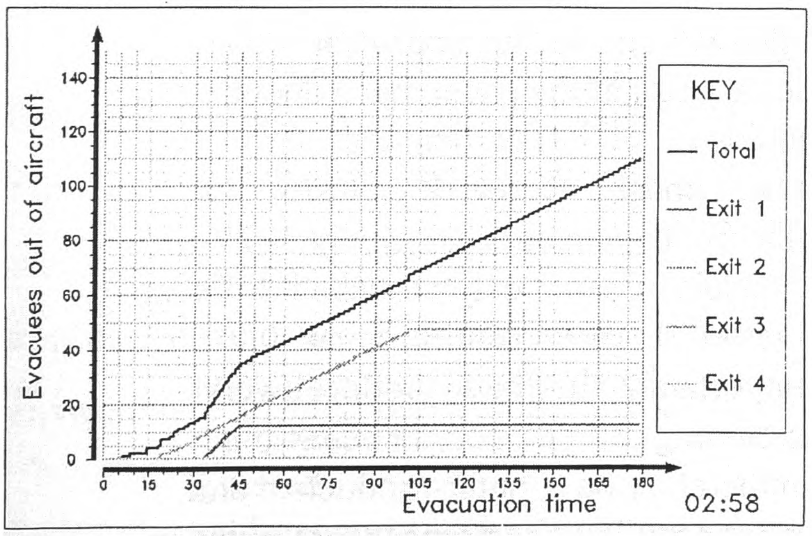


Figure 10: an example graph generated by Macey's model

As mentioned previously the model was designed to simulate a range of empirically determined scenarios in order to ascertain a level of risk for a particular configuration. In order to validate the models, the designers contrived probabilities so that a scenario was selected that was equivalent to the 90-second certification trial. Using a certification trial configuration, four different aircraft were modelled. Two of these were compared to the results of 90-second certification trials. In both cases the model predicated an evacuation time that was within 10% of the certification trial (see Table 2). In addition in both cases the results of the model were higher than that of the certification trial. The model designers stated that the over estimation by the model was due to passengers having to open the exits and exit overcrowding. The lack of cabin crewmember redirection led to sub-optimal evacuations that caused the overcrowding at some exits. In addition, from the validation results (see Table 2) it is apparent that only one time was presented for the validation results.

Table 2: The validation history of Macey's Risk Assessment Model (reproduced from [77])

Aircraft Type	Seats	Actual Time	Model Time
A320	179	79s	85.0s
A321	224	-	81.2s
B757	219	73.5s	77.8s
B737-800	189	-	91.8s

2.2.3.8 Oklahoma Object Orientated model (OOO)

In the mid 1990's Mary Court from Oklahoma University and Jeff Marcus from CAMI published a design specification for an Object Orientated evacuation model. Whilst the model itself was never actually developed, the design is described in this section.

The proposed model was for a (fine network based) simulation model with an individual population perspective and rule based behaviour. The model was intended to be able to simulate both real emergency evacuations and 90-second certification trials. It was the designers wish that the model ran in real time (if possible), that the model generates output suitable for detailed analysis and animations for the purposes of presentations.

Required features were that the model was able to simulate group relationships, i.e. families and work colleagues, cabin crewmembers and associated passenger management issues, that the behaviour of passengers and crew adapted during the evacuation and to a dynamic thermo-toxic environment, that the thermo-toxic environment affected behaviour and also the physiology of the passengers and crew.

From these requirements an Object Oriented (OO) design was created (see Figure 11). The design contained three modules. The passenger scenario module allowed the user to build the passengers within the scenario. Within this module personal attributes such as, age, sex, height, weight, etc. relationships could be specified for passengers and cabin crewmembers. The layout module was used to construct the cabin geometry. Using this model seats, monuments and exits could be specified. In addition passengers could be assigned to specific exits within the model. The cabin environment module allowed the thermo-toxic environment within the cabin to be generated.

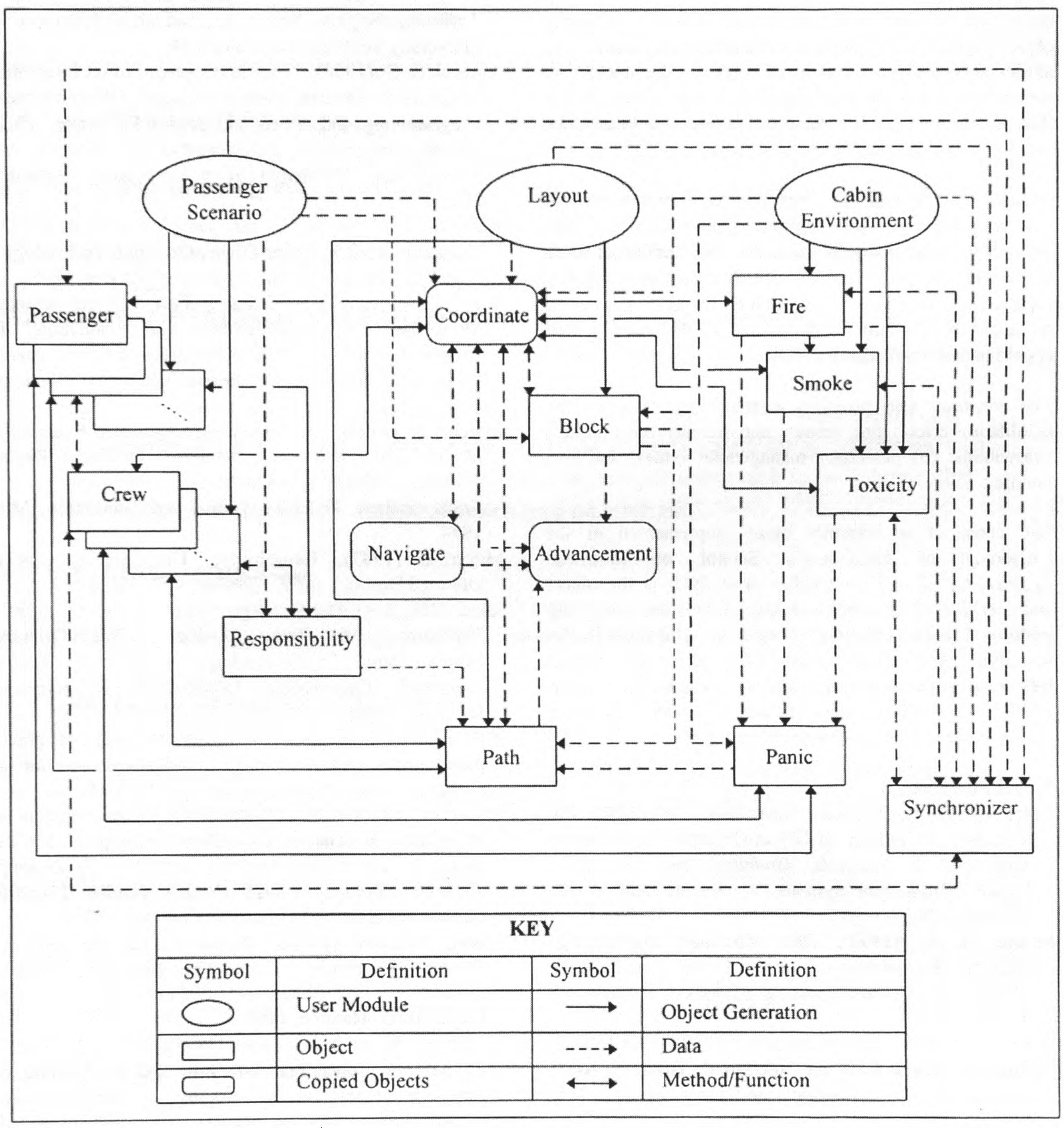


Figure 11: The proposed OOO model design [79]

The OO model was comprised of 13 classes (objects or copied objects within Figure 11). The SYNCHRONIZER class was the controlling class that coordinated all of the other classes/objects within the simulation. Many instances of the PASSENGER and CREW classes were generated according to the desired number within the scenario. They would each have their own defining attributes and relationships with other passengers. The COORDINATE object distributed the aircraft geometry to other objects, i.e. to passengers, crew, fire, smoke and toxicity whilst sharing data with others: NAVIGATE, ADVANCEMENT, PATH and BLOCK. The BLOCK class contained information about obstacles such as seats, walls, other passengers and crew in addition to environmental obstacles such as smoke and fire. The NAVIGATE class was responsible for choosing the headings for actors, i.e. passengers and/or crew. This was affected by their cognitive and physical abilities. The PATH class would assess available paths/routes that passengers and crew could take during an evacuation. This would be affected by the geometry, their location within the cabin, fire, smoke, toxicity and their cognitive abilities. The ADVANCEMENT object was responsible for moving passengers between locations within the simulation. Information regarding the FIRE, SMOKE and TOXICITY classes was not provided. Presumably, they would manage the growth of these hazards. Depending upon the type of scenario, some of the classes would not be required. For example, in a 90-second scenario the fire, smoke, toxicity and panic classes would not be required.

The RESPONSIBILITY class allowed information sharing between objects. For example, cabin crewmembers were given access to some of the attributes of passengers and greater knowledge of the cabin layout. Related passengers may be assigned responsibilities, such as parent and child relationships. Finally, the PANIC class would affect the actors' ability to reason, i.e. they may make poorer decisions if they were panicked.

The model design did not specify how the behaviour of passengers was affected when using exits or escape slides or how they would be modelled. Furthermore, no indication was given on how model parameters would be determined. Finally, as the model was never developed no validation was performed. As such the model's abilities are unknown.

2.3 A critical evaluation of aviation evacuation models

Having discussed evacuation models and their data, this section critically evaluates the aviation evacuation models. The key characteristics of the aircraft evacuation models are summarised in Table 3 and Table 4.

Table 3: Summary of Aviation Evacuation Model Methodologies

Model	Nature of application	Enclosure representation	Behavioural Perspective
GPSS	SIMULATION 90-SECONDS	COARSE	INDIVIDUAL & STOCHASTIC
GA	SIMULATION REAL EMERGENCIES	FINE	INDIVIDUAL & STOCHASTIC
ARCEVAC	SIMULATION BOTH	FINE	INDIVIDUAL & STOCHASTIC
EXODUS	SIMULATION BOTH	FINE	INDIVIDUAL & STOCHASTIC
DEM	SIMULATION BOTH	FINE	INDIVIDUAL & DETERMINISTIC
MACEY	RISK ASSESSMENT BOTH	FINE	INDIVIDUAL & DETERMINISTIC

Table 4: Summary of Aviation Evacuation Model Features, Validation History and Parameter Basis

Model	Hazard representation	Toxicity representation	Cabin crewmember procedures	Validation history	Parameter Assignment
GPSS	NONE	NONE	Implicit	4*90S of which 1 was unsuccessful	EMPIRICAL
GA	ZONE	SIMPLISTIC	Implicit	3*RE	ARBITRARY
ARCEVAC	ZONE/Arbitrary	NONE	Both	1 *90S	ARBITRARY
EXODUS	GRID/experimental or 3D model based	FED	Both	8*90S (1*Blind 90S), 2*EX	EMPIRICAL
DEM	NONE	NONE	None	1*RE	ARBITRARY
MACEY	GRID/2D model based	FED	None	2*90S+ / (4*90s)	ARBITRARY

+results of the certification trial was only known for two of the four validation exercises

2.3.1 Basis of Model Parameters

As mentioned previously, evacuation models are only as good as the data that is used in their formation. The methodology that a model uses in specifying key parameters is therefore of critical importance.

Some models, such as DEM, GA, ARCEVAC and MACEY use essentially ARBITRARY estimates to determine values for model parameters. For example, GA and ARCEVAC use an arbitrary probability of a passenger passing through an exit to determine the exit hesitation delay. Whereas, DEM specifies this delay indirectly through allowing only one passenger to descend each escape slide at any one time. MACEY's model is somewhat unusual in that empirical data is extensively used in determining the likely scenario (see Section 2.2.3.7), however little empirical data is used in the evacuation sub-model itself. Gaining confidence in models that have arbitrary parameters is difficult, as their results have no real world basis. For example, what does it mean in GA when a passenger dies having been exposed for 40 seconds to a 120 toxic hazard exposure?

GPSS and EXODUS make use of EMPERICAL data in specifying model parameters. In both models Exit Hesitation Delays are specified from analysis of the actual event. Within EXODUS numerous parameters are empirically determined, such as exit preparation time, passenger response time, passenger movement speeds, etc. As such, greater confidence can be gained in the results of the model as it is fundamentally based on empirical studies, i.e. reality.

2.3.2 Validation/Verification history

Confidence in any model is gained through its accuracy at reconstructing or predicting what happens in reality. Thus a convincing record of verification/validation is essential. Indeed, software validation should be considered as an on-going activity. For any complex simulation software, validation is not a 'once and forget' task, but should be considered as an integral part of the life cycle of the software.

The verification/validation of evacuation software is no exception. Indeed, the lack of a large battery of convincing data for the verification of evacuation software has meant that a rigorous procedure needed to be established for the validation/verification of evacuation software. Such a procedure has been outlined by Galea *et al* [96], and adopted by the building and maritime industries [97, 98]. This procedure can be readily adapted for use in the aviation industry and is outlined here.

There are at least four forms of validation/verification that evacuation models should undergo. These are COMPONENT, FUNCTIONAL, QUALITATIVE AND QUANTITATIVE verification.

Component verification involves checking that various components of the software perform as intended whilst functional verification involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the desired simulations. The third form of model verification concerns comparing the nature of predicted human behaviour with informed expectations. While this is only a qualitative form of validation, it is nevertheless important as it demonstrates that the behavioural capabilities built into the model are capable of producing realistic behaviours. Quantitative verification involves comparing model predictions with reliable data generated from an evacuation demonstration. At least two types of quantitative verification may be performed. The first involves the use of historic data. In this case the user performing the verification has complete knowledge of the experimental results. The second type involves using the model to perform predictive simulations prior to having sight of the experimental results, a so-called "blind" prediction.

In practice, quantitative verification of aircraft evacuation models is accomplished by comparing model predictions with results of real world events, such as EXPERIMENTS (EX), 90-SECOND TRIAL (90S) or REAL EMERGENCY (RE) evacuation situations.

The most confidence can be gained through comparing models against the results of carefully controlled experiments that are repeated a number of times. The second most effective data source for validation is the 90-second certification trial. However, as mentioned previously they are not ideal as they generate only one data point on a hypothetical distribution of probable results (see Section 2.4.1). Even greater confidence can be gained through performing 'blind' simulations (B). In other words running the model before the results of the trial are known. Finally, real emergency evacuations are extremely difficult to use for quantitative verification as not only do they generate only one data point, but the precise conditions of the emergency are never known to the level required by the modeller to establish correct starting or environmental conditions and the actual evacuation times are seldom known to the degree of precision required.

2.3.2.1 Verification history of surveyed aviation evacuation models

The GPSS software has been subjected to four quantitative validation exercises. In these cases four blind 90-second certification trial (4-B90S) evacuations were used. In three cases (L1011a, L1011b and L1011c) it predicted the result of the trials with what was deemed by the authors as *"reasonable accuracy"*. However, in one case (the B747) it performed poorly. This was attributed to variation in the performance level of passengers and crew during this trial.

The only verification of the GA model that is known concerns the qualitative verification using three real emergency evacuations (3-RE) the, DC-8 at Denver in 1961, B-727 Salt Lake City in 1965, and the DC-9 Denver 1976. These verifications are considered qualitative, as reliable times for the actual emergency evacuations cannot be established, nor precise starting conditions. Furthermore, the results of this exercise were not published.

Quantitative verification of the ARCEVAC model was performed using a single certification trial of Canadair Regional Jet (CL-65) after the trial had taken place (1-90S). Due to the proprietary nature of the actual certification trial data the model developers could not cite the total evacuation time for the trial. They merely state that their model generated an evacuation under 60 seconds.

The results from a single quantitative verification trial of the DEM have been published. This involved an evacuation analysis of the 90 second certification trial of a B737 aircraft (1-90S). In this case, DEM predicted a single evacuation time of 81 seconds, which was within 6 seconds of the time generated by the actual 90-second certification trial [94,71].

Quantitative verification of the MACEY model has been accomplished using four certification trials (4-90S) of which the results of two are known. In both of these cases the model predicted a single evacuation time that was within 10% of the actual time generated by the trial. Furthermore, in both cases the model over estimated the time generated by the certification trials.

EXODUS has a published verification history that incorporates all four validation components. Quantitative verification has been achieved using the results of 2 experiments (2-EX) [45] and 1 blind prediction for a wide-bodied aircraft [45] (2-EX, 1-B90S) [49]. These validation tests have shown the model to correlate well with reality. However more validation is required to increase confidence in future model predictions.

Finally, it should be noted that it is extremely difficult to make any sense of validation performance when models use arbitrary data sets. As the data is arbitrary, it can be artificially changed from one simulation to another. The results should therefore be presented with a description of the changes made to the parameters.

2.3.3 Discussion

Originally designed in the 1970's, GPSS is now very dated in terms of platform (Large mainframe computers) and capabilities. It contains little human behaviour with the result that passengers behave like mindless ball bearings [95]. Whilst making use of empirically determined exit delay distributions, they were cited by the authors as being inadequate by its validation exercise. Finally, the model was only validated against four certification trials, of which one showed poor correlation.

DEM assumes passenger movement to be analogous to Newtonian soft spheres. As such passengers shape is assumed to be round. This model treats the movement of passengers much like ball bearings, an approach that is now considered dated [95]. In addition, some of the assumptions on which the model is based undermine its ability to reflect reality accurately. For example, one of the assumptions is that only one passenger may use an escape slide at any one time. This is not necessarily the case, as more than one person can occupy slides simultaneously. In addition the logical consequence of this approach is that for much of the simulation the length of the slide determines the flow rate through the exit. The rationale for this is unclear. Firstly, the relationship between slide length and flow rate has not been shown. In addition numerous passengers frequently occupy a slide at a time. This assumption alone undermines the results of the model. This casts serious doubts on the usefulness of the validation exercise presented in support of the model.

The GA model demonstrated many of the qualitative behavioural features of real emergency evacuations. In terms of qualitative features it included a more comprehensive representation of the behaviour than either GPSS or DEM. In addition the GA model had a rudimentary toxicity and hazard model. However, the main criticisms of the GA model are that their model parameters were not empirically determined and that their hazard and toxicity models were completely arbitrary. As such it is difficult to derive meaning from the results. Another failing was that cabin directed bypass was performed via the manual operation of the keyboard during a simulation. Finally, the model was only capable of simulating the evacuation of narrow-bodied aircraft. These failings were compounded by the lack of validation performed on the model.

ARCEVAC contained numerous complex behavioural features that distinguished itself from other evacuation models of the time. ARCEVAC, provided an explicit representation of cabin crewmembers that were capable of performing complex procedures (such as checking aisles or seats) whilst the simulation ran. In addition ARCEVAC offered a mechanism of representing the state of mind of simulated passengers, via a state attribute, and contained 'social attributes', such as dominance, selfishness, etc. Whilst containing numerous behavioural capabilities it may be criticised, as its behaviours were not based on empirical evidence from experiments or air accidents. In addition, the model was limited to simulating the B727 aircraft, although other aircraft may have been possible if the code was rewritten. Finally, the ARCEVAC model was only validated once and the results were unclear.

EXODUS contains a large number of behavioural features and capabilities. However its behaviour set does not fully represent everything that could happen in an emergency evacuation or indeed a certification trial. With respect to simulating 90-second certification trials, its model parameters are based on comprehensive research [90] relating to previous certification trials. It is arguable whether all of the human performance data generated from certification trials is relevant to accident applications. The model attempts to use such data in addition to data derived from accident investigations and laboratory based experimental trials for accident related scenarios. EXODUS has been validated against numerous certification trials and experiments, two of which were performed blind. EXODUS is capable of simulating the evacuation of narrow-bodied (NB), wide-bodied (WB), double deck (DD) and blended wing bodied (BWB) aircraft. This model treats each person within the simulation as an individual allowing them to follow and adapt their individual evacuation strategies. Whilst, the behaviour within EXODUS is comparatively comprehensive, it does not cover the full range of behaviours that may be found in actual accidents. This is mainly due to the lack of reliable data upon which models can be formulated. Future development should be focused on a range of activities including the study and development of behaviour exhibited in real accidents, the quantification of behaviour during real emergency evacuations and the further development of the models capabilities to simulate 90 second certification scenarios.

Like many other evacuation models, MACEY's risk assessment model suffers from arbitrary parameter assignment. Whilst a wealth of empirical data was used in setting the scenario, very little empirical data was used within the evacuation sub-model. As such, the performance of components such as exits were imposed on the model rather than generated by the model as results. In addition, whilst the model was capable of simulating evacuation via aircraft fuselage ruptures no data was employed in representing the delays that passengers were likely to experience in negotiating them. As the designers conceded the exit flow rates would not be appropriate in real emergency accidents. Furthermore the model completely ignored cabin crewmembers. Consequently, passengers prepared exits for use. During the validation exercise, this was cited as a possible reason for the model continually over estimating evacuation times. Finally, the Macey model makes use of two-dimensional fire and airflow sub-models. These are extremely simplistic and are incapable of reproducing important fire effects such as smoke layering.

2.4 Data for Evacuation Models

Associated with the development of computer based evacuation models is the need for comprehensive data collection/generation related to human performance under evacuation conditions. The nature of the particular type of scenario to be simulated will dictate the type of data required and the capabilities the model will require. Factual data regarding the evacuation process is essential to the development of computer evacuation models. Evacuation models have a high reliance on factual data regarding the evacuation process in order to:

(a) Identify the physical, physiological and psychological processes that contribute to, and influence the evacuation process and hence inform the formulation of appropriate models (examples of relevant processes include seat jumping, aisle swapping, family group coherence, movement in smoke, incapacitation due to inhalation of toxic products etc.)

(b) Quantify attributes/variables associated with the identified processes.

(c) Provide data for model validation purposes.

Three forms of data are useful in providing the required information. Accident reports containing interviews with accident survivors, video footage from 90 second certification trials and data generated from full-scale and component experimentation. Each of these data sources provides useful information for modelling.

Accident investigation reports that contain human factors analysis and survivor interview accounts are vital in providing information to identify the human element (i.e. item (a) above) that needs to be simulated if the model is to be used in performing simulations of realistic accident scenarios. Equally, data from 90 second certification trial videos can provide similar information suitable for models intending to simulate certification trials.

Once identified, the behaviours and performance attributes must be quantified (i.e. item (b) above). For models intended to simulate real incidents a useful form of data is derived from full-scale and component tests. This is necessary as reliable quantitative data from real emergency evacuations does not exist - there are no cameras positioned to record proceedings. In these circumstances, experiments must be contrived to replicate accident type situations without putting participants at risk of injury. The quantification of the identified attributes may involve collating probabilities of specific actions, such as seat jumping, measuring the time taken to perform specific actions, such as exit openings, passenger exit hesitation, etc. When undertaking experimentation, it is essential to ensure that a representative population is used for data collection. Often in performing evacuation experimentation specialist sub-populations such as students or military/police personnel or single gender groups are used. The results generated from such experiments are not likely to reflect the performance capabilities of the intended target population and as such are of questionable value.

For models intended to simulate 90 second certification trials, detailed analysis of video footage from trials can be used to quantify the identified attributes (i.e. item (b) above).

Finally, data is necessary to validate the predictions of evacuation simulations. Ultimately, the worth of a model is gauged against its ability to realistically and accurately reconstruct and/or predict the real world. Again, data from 90-second certification trials and contrived experimentation can be used to validate models.

2.4.1 Data from 90-second certification trial evacuations

By detailed study of video recordings from 90 second certification trials, both qualitative and quantitative data can be generated relating to passenger behaviour. From the analysis of videos of 90-second certification trials it is possible to establish various behavioural traits common to certification trials. For example, passengers spend an insignificant amount of time in releasing seat belts, very little aisle swapping occurs, passengers are very compliant to crew instructions, seat jumping is extremely rare, passengers hesitate at slide exits prior to committing to jump, etc. It is important to note that while these behaviours are extremely relevant to certification trials they may be completely irrelevant in real accident situations. In addition, it is possible to quantify passenger attributes identified in the 90 second trials. For example, the flow rates and movement velocities of passengers in aisles, the passenger exit hesitation time for various exits types, time to traverse slides, time to open an exit, etc. This type of data is essential if models are faithfully to reproduce the type of behaviour seen in certification trials.

It is however extremely difficult to obtain access to this type of data as the aircraft manufacturers that produce the data consider it to be valuable proprietary information that would provide advantage to their competitors. However, FSEG of the University of Greenwich with sponsorship of the UK Civil Aviation Authority and through strict confidentiality agreements with all the major manufacturers (i.e. Airbus Industries, Boeing Commercial Airplane, British Aerospace, and Douglas Aircraft Company Inc (McDonnell-Douglas (MDC) Corporation) has access to all the 90 second data video footage that exist. This information has been analysed by FSEG and forms an integral part of the airEXODUS model [90,91]. While the regulatory authorities have access to this data it is not generally available to other model developers.

In total some 30 evacuation trials of 24 aircraft have been analysed, that cover the period 1969 to 1996 and include commuter, single aisle, dual aisle and double deck aircraft. The data represents the evacuation of 68 Flight Crew, 194 Cabin Crew and 8865 passenger participants.

The data extracted concerns exiting behaviour of the passengers and crew on an aircraft by aircraft and an exit by exit basis. From the data the following information was collated: Cabin Crew Response Times, Exit Opening Times, Slide Inflation Times, Exit Ready Times, Passenger Exit Use, Passenger Exit Hesitation Times, Passenger Escape slide / Wing Use `Off Time', Flow Rates, efficiency measures and Type-A Exit Lane Usage. This data has been presented in tabular form for each aircraft investigated.

Furthermore, the data provides a means to validate models designed to simulate 90 second certification trials. This is enabled by a thorough knowledge of; the starting conditions for each evacuation, the end times for each exit, the number of people to use each exit, the location of bottlenecks, flow rates through exits, etc.

Whilst these video records do provide much of the data required for the development and testing of models intended for the simulation of certification trials, the data is not perfect. Two main shortcomings are apparent.

Firstly, data generated for certification trials were not intended for computer model development. Thus, they are not carried out in the controlled experimental manner that would be most desirable for model development. Consequently, there is very little control over variables examined in the trials and modellers have to contend with "gaps" in the data. For instance, there may be insufficient data available covering all possible combinations of cabin crew assertiveness and exit type.

2.4.2 Data from aircraft accident/incident reports

Unlike certification evacuations, in real emergency evacuations passengers are subjected to very real psychological, physiological and physical threats that may engender competitive behaviour (as opposed to the co-operative behaviour seen in certification trials – see section 2). Consequently, the modelling of actual behaviour and events during real aircraft accidents is far more challenging than the simulation of certification trials. It also means that the collection of data describing and quantifying this behaviour is also much more challenging - unlike 90-second certification trials and experiments, in real aircraft accidents there are no cameras positioned to record proceedings!

Given the fact that the 90-second certification trial is not an accurate measure of evacuation performance during real emergency evacuations [1] (see Section 2.4.1) it is necessary to identify potential sources of data describing and quantifying behaviour in real emergency evacuations. A source of information concerning human behaviour in aircraft accidents is provided through aircraft accident human factors reports produced by organisations such as the NTSB of the USA and AAIB of the UK. These reports contain a wealth of information in the form of interviews with survivors (crew and passengers). The information is collected and documented to aid in the investigation of the accident. However in themselves, individual accident investigation reports do not provide a means to extract reliable generalities concerning actual human behaviour in a range of evacuation situations.

In developing evacuation models capable of simulating real accidents, it is vital to understand the phenomena that are to be modelled and to take a scientific approach to its understanding. One of the first relevant systematic studies was undertaken in 1970 by Snow *et al* in which they analysed four air accidents to highlight common factors that influence survival [99]. This paper concluded that configuration, procedures, the environment and passenger behaviour were vital in understanding survival. This work was the first attempt at building an empirical understanding of the dynamics of real emergency evacuations, and is an approach that is widely used today.

While several systematic studies [100] and databases [101] concerning aircraft accidents have been developed, these have concentrated on the details of the accident rather than on the nature of the resulting human behaviour. To date there have been two detailed studies into human behaviour over a range of accidents, one, an on-going study by FSEG of the UK known as the AASK database [102,103,6,7] and another by the NTSB of the USA covering a number of recent accidents and pre-cautionary evacuations [3].

The information available in these studies is based on air accident investigation reports and the passenger and crew testimonies that they contain. This data tends to take the form of anecdotal evidence, sometimes with third party corroboration. Using this data insight into the behaviour of passengers and crew during real emergency evacuations can be gained and appropriate behaviours and/or modifications to existing behaviours made within evacuation models. Thus, a model that is more realistic to real emergency evacuation can be developed.

2.4.2.1 The AASK database

The AASK database has been developed by FSEG of the University of Greenwich with financial support from the UK CAA. This is an on-going project with work commencing in 1993. The AASK database is a repository of survivor accounts from aviation accidents. Its main purpose is to store observational and anecdotal data from the actual interviews of the occupants involved in aircraft accidents. With support from the UK CAA, the AASK concept has evolved into an on-line prototype system available over the internet to selected users. The current release of AASK is V3.0.

Data contained within AASK V3.0 consists of information derived from both passenger and cabin crew interviews, information concerning fatalities and basic accident details. The cabin crew component has become a significant aspect of the database providing insight into cabin conditions and passenger behaviour as seen from professionally trained cabin specialists. The fatalities component holds data for all fatalities documented in the accident reports while the Seat Plan Viewer graphically displays the starting locations of all the passengers – both survivors and fatalities - as well as the exits used by the survivors.

Data entered into the AASK database was extracted from the transcripts supplied by the Air Accident Investigation Branch in the UK and the National Transportation Safety Board in the US. The quality and quantity of the data was very variable ranging from short summary reports of the accidents to boxes of individual accounts from passengers, crew and investigators. Data imported into AASK V3.0 comprises information from accidents that occurred between 4/4/77 and 8/3/98. This consists of:

- 55 accidents,
- 1295 individual passenger records from survivors,
- 110 records referring to cabin crew interview transcripts, and
- 329 records of fatalities (passenger and crew).

2.4.2.2 The NTSB Accident Survey

The US National Transport Safety Board (NTSB) has completed a recent data collection exercise from September 1997 to June 1999 involving 46 evacuations, 2,651 passengers and 18 different types of aircraft.

The study examined a range of evacuation aspects. Evacuees (passengers and crew) were surveyed in order to ascertain their views on the evacuations and to answer specific questions concerning the evacuation performance. The study investigated the following issues concerning exits and evacuation issues in general: access to the exits, emergency lighting, Type-III over wing exits, exit row passenger tasks, flight crewmember exit assignment, evacuation slides, exit height from the ground. In addition evacuation procedures were examined specifically those for planned evacuations, exit selection, slide commands, aircraft familiarisation, and guidance on when to evacuate. Finally the report examined communication issues between crewmembers, passengers and crewmembers.

This report contains some useful data for evacuation modellers. Firstly, information concerning the nature of probable types of evacuation scenario is presented. Data of this kind is essential in developing a holistic approach to certification, i.e. one that takes a performance-based approach considering the evacuation performance of the aircraft under representative scenarios. For example, of the emergency situations utilising escape slides, 37% of the cases experienced problems with at least one escape slide. In addition, the report states that in 3 of the 13 evacuations that utilised Type-III exits, passengers experienced difficulty. Furthermore in one of the three cases, an elderly passenger was unable to operate the exit at all.

Secondly, the report contains useful qualitative data on evacuations. For example, of those passengers that carried baggage onto the aircraft, nearly 50% of passengers reported attempting to evacuate with at least one item of their luggage. This is quite significant as some 66% of the interviewed cabin crew cited carry-on luggage as an obstruction and 37% of passengers thought that carry-on luggage slowed their evacuation. During 90-second certification trials passengers have no carry on luggage although some luggage is distributed within the cabin to simulate accident debris. Thus, in 90-second certification trials these sorts of delays do not manifest.

2.4.2.3 The limitations of anecdotal evidence from air accidents reports

Whilst, anecdotal data from real aircraft accidents - be it from the AASK database or from passenger testimonies themselves - are useful for the identification of behaviours and to some extent their quantification, this type of data has limited scope for quantifying time-scales of events and for the validation of evacuation models in general.

Deriving definite time-scales of events during real emergency evacuations is difficult. Instead, temporal data takes the form of rough estimates from the testimonies of surviving participants, rescue workers and, depending upon the location of the crash, accounts from spectators with timing facilities such as airport towers or other flight crew as in the Manchester air crash [10].

As a consequence, vitally important pieces of data such as the length of time taken to open exits, unbuckle seat belts, etc is extremely difficult to obtain with certainty. Whilst it is extremely difficult to obtain accurate time-scales, it is not as difficult to gain an understanding of the likely occurrence of specific events, i.e. behaviours and events, through the frequency of their citation within testimonies and corroboration from others involved. However, in this context anecdotal evidence, in the form of personal testimonies, is only available from surviving passengers. Consequently, the behaviour of passengers that perished in the incident is limited to second hand observation from survivors. The data is therefore skewed towards the successful or survival behaviours.

As a result, full-scale and component experiments have been performed to better understand and quantify the performance of simulated real emergency scenarios.

2.4.3 Controlled evacuation experiments.

Due to the inherent limitations of certification trials and accident analysis, large-scale experiments and component tests offer an alternative source of data for model development. While a number of evacuation experiments have been carried out, to date, their primary purpose has been to address operational or regulatory issues. As their primary purpose was not to collect data to assist in the development of evacuation models, the data generated is often less than ideal for modelling purposes.

Nevertheless, this data can and is being used in the development of computer models. Depending on the nature of the experiment, this data can be used in the development of certification applications and for real accident applications. The data can also be used for all three components of model development identified in Section 4.

2.4.3.1 Large Scale Test Facilities

There are currently two major facilities capable of undertaking large scale or full-scale aircraft evacuation tests on a regular basis. These are located at the Civil Aero Medical Institute (CAMI) in the USA and Cranfield University in the UK.

CAMI led the world in developing a reusable large scale test facility for evacuation analysis. The CAMI cabin simulator – developed in the 1960's - consists of a C124 fuselage section, 12 feet wide and 77 feet long, mounted on hydraulically controlled platforms so that various pitch and roll conditions can be simulated [105,106]. This test facility has been extensively utilised in the last 30 years "answering questions concerning seating density, exit size and location, passenger flow rates through exits, and flight attendant behaviour" [106].

CAMI hope to replace this test facility with a "Flexible Cabin Simulator" (FCS) [107]. The proposed simulator will be mounted on hydraulics, so as to simulate various door and sill heights, the FCS will be capable of simulating Wide-Bodied (WB), Narrow-Bodied (NB), Blended Wing Bodied (BWB), Double Deck (DD) and Mega Bodied (MB) evacuations onto land or sea, via a purpose built water tank.

Cranfield University currently has two active cabin simulators. The first is a B737 capable of simulating NB aircraft evacuations and the second, the Very Large Evacuation Simulator (VLES) funded by the UK CAA, is of flexible modular design and is capable of simulating WB, BWB, DD and MB evacuations [108]. The VLES opened on the 12th of July 2001 and is 36 feet wide (11 metres), 82 feet long (25 metres) and 32.8 feet (10 metres) high and is the first of its kind. In addition Cranfield had previously used a Trident Three aircraft cabin section to simulate narrow-bodied aircraft evacuations. The Trident Three evacuation simulator has now been decommissioned following the construction of the B737 test simulator.

These facilities have been used to perform numerous experiments to better understand human performance in evacuation situations. Some trials have been performed under non-competitive behaviour and so are similar in nature to the certification trial while other trials have been performed under competitive behaviour – a technique pioneered by Cranfield University – in an attempt to simulate the conditions of real evacuation situations. A brief summary of these experiments is outlined in this section.

Early CAMI research

There has been much research carried out using the CAMI cabin simulator. Since the Manchester air disaster of 1985, this facility has investigated topics such as effects of exit size, passenger abilities, platforms and exit approach configurations of Type-III exits on evacuation performance [109,111-120]. These trials have included techniques to simulate competitive behaviour pioneered at Cranfield (see Section 2.4.3.1). Before discussing these more recent trials - that make use of the variations of the Cranfield methodology - the early work of CAMI will be discussed.

(a) Early attempts at simulating emergency conditions

In 1966, Garner and Blethrow of the FAA undertook the first evacuation exercise under simulated 'emergency' conditions [121]. The cabin section that was utilised was a Lockheed Constellation L-1649 fuselage that had recently crashed. The aircraft had crashed on a hill and had split into three pieces. Following the crash the wreckage was restored to "a practical and safe specimen" [121] for use in evacuation experiments.

The experiment that was conducted made use of emergency lighting, dense white non-toxic smoke, outside flashing strobe lights at the rear of the aircraft and prior to the evacuation some simulated engine noise. The evacuation scenario also involved cabin crew, simulated injured passengers that needed rescue and ropes at over wing exits. The aircraft also had an uneven orientation. To a passenger moving forward the pitch of the front section was six degrees downwards and the mid-section and aft section were 20 degrees and thirty-two degrees upwards respectively. For safety reasons, only half of the middle and all of the aft sections were used in the experiment.

This experiment was of qualitative value in revealing a multitude of human behaviour that may occur in real evacuation situations.

(b) The effects of aircraft attitude

Using their test facility CAMI in 1978 analysed the impact of landing gear failure upon evacuation performance [105]. This was achieved using the hydraulic capability of the CAMI facility to achieve various combinations of pitch and roll. The analysis was performed in order to ease concern over the performance of B747 style staircases during emergency evacuation. In total CAMI performed 210 trials, with subjects evacuating through spiral and straight-segmented staircases, passageways with seats on one side and without seats on both sides, both with and without simulated smoke via light obscuring goggles.

During these experiments a different subject population, typically between 23-26 (depending upon attendance), was obtained each of the seven trial days. Each population performed 30 trials on each of the days. Each sub-population was subjected to a different series of scenarios on each day.

The trials were conducted under non-competitive conditions. Thus, while the behavioural regime is similar to a certification trial, the actual scenario investigated i.e. uneven floor, is more akin to real accident situations.

Their findings provide useful information with respect to the qualitative performance of passengers during these trials. However, in their experiments volunteers were required to traverse the experimental apparatus in both directions, i.e. up and down the stairs and forward and aft of the passageway. Unfortunately, in the published report [105], flow rates are presented for the combination of both movement directions. As such the data is of little use to evacuation modellers, as information cannot be extracted for motion in a single direction.

This information is of vital importance to the simulation of real accident scenarios and it is hoped that these experiments will be repeated and data useful for model development generated.

(c) Evacuation performance of disabled passengers

The FAR 28.803 emergency demonstration does not require the inclusion of passengers with movement disabilities. As such, no information regarding the evacuation of disabled passengers is available from 90-second certification trials. While some information is available on the performance of disabled passengers in accident reports, this information provides no quantitative data on movement rates.

In 1977, CAMI performed a series of trial evacuations using various different categories of disabled passengers. In total 153 subjects were used of which 129 had some form of disability. Disabilities included quadriplegics, blindness, partially sighted, cerebral palsy, elderly, deafness, mental deficiency, leg casts, obesity, multiple sclerosis, polio, arthritis, birth defects, paraplegic and via anthropomorphic dummies the non-ambulant.

Useful quantitative data was generated concerning the extended response times of the disabled passengers, their slower movement speeds through aisles and seat rows and large exit hesitation delays. In addition, qualitative trends such as the requirement for cabin crew and/or carer assistance during the evacuation and the propensity for 'sub-queues' [118,36] to form behind slow moving passengers were revealed as well as fatigue effects [118]. This data is of great importance to modellers attempting to simulate real evacuation situations.

Techniques for simulating competitive evacuation

Following the Manchester air disaster of 1985 and as part of a UK CAA funded research programme, Prof Helen Muir and others from Cranfield University pioneered a new technique to simulate 'competitive behaviour' of the type reported in emergency evacuations [92,122,124]. The technique involved giving £5 bonus payments to the first 50% (later increased to 75% in some experiments) of passengers to evacuate a Trident aircraft fuselage used as a full-scale cabin simulator. Muir later concluded that the technique was successful, stating that,

"The experimental programmes had successfully demonstrated that it was possible to develop new techniques to simulate the behaviour which can occur in aircraft emergencies involving life threatening situations..."[128].

Using these techniques Muir went on to investigate the effects of bulkhead widths [122-124,128], seating configuration [122-126,128] and cabin crew motivation [92,127,128] adjacent to exits. Results of this work indicated that, contrary to the prevailing theories of the time, the flow rate of passengers through constricted areas of the cabin was lower when the passengers behaved competitively, i.e. similar to real emergency, than when they behaved in an orderly manner, as in 90-second certification trials. This hypothesis was also found to be true in the presence of non-toxic theatrical smoke. From the modelling perspective this data serves as a useful indication of the likely performance during real emergency evacuations.

In addition, Muir also found that the presence and motivation of assertive cabin crew tended to increase the flow rate of passengers through floor level aircraft exits [92, 127,128]. The Cranfield analysis was restricted to Type-I exits as this was the only floor level exit with crew support. This result is similar to the FSEG finding concerning passenger exit hesitation times based on the analysis of 90-second certification data for Type-I and Type-A exits [90,91].

Research still needs to be undertaken to compare passenger exit hesitation times generated from competitive experimental trials and 90 second certification trials. This is of importance as it may be possible to use certification data concerning exit hesitation times for real accident applications.

Experiments involving Type-III exit performance

Subsequent to the Manchester air disaster of 1985, numerous experiments have been conducted both at CAMI and at Cranfield University during the period 1989-2000 concerning Type-III exits. Some of the relevant findings are briefly summarised in chronological order below.

Initially in 1989, Rasmussen et al based at CAMI attempted to determine the effects of seating configuration adjacent to Type-III exits on the exit hatch removal and egress [109]. Of the configurations examined it was concluded that the dual 6" passageway was significantly faster than the single 6" ($p<0.005$) and 10" ($p<0.01$) passageway configurations. Another finding of this work was that exit hatch removal and disposal was not greatly affected by passageway configurations. From an evacuation modelling perspective these experiments provide some useful quantitative and qualitative information on exit preparations and likely exit flow rates against which evacuation models could be validated. However, the data was not presented in a form useful for evacuation modellers. If video footage of these trials were made available, exit hesitation delays could be extracted as could passenger movement rates and movement behaviour appropriate for the exit configuration.

McLean et al followed these experiments in 1989 with an investigation of the effects of wearing smoke hoods on evacuations through type-III and Type-IV exits in smoke and clear air [110]. This study found that evacuation through the Type-III exit was faster than through the Type-IV exit ($p<0.005$). It was found that wearing smoke hoods increased the egress time through both types of exits ($p<0.05$). Furthermore, other factors such as size of the exit and smoke hood and passenger learning influenced individual evacuation times. In its current form, this work provides useful qualitative information and some quantitative information, in the form of a performance decrement, on passenger evacuation through these types of exits. Here again, video footage of these evacuations would assist model developers in assessing exit hesitation curves for evacuations in the presence of non-toxic smoke, both with and without smoke hoods.

In 1989, Muir et al first utilised the monetary payment technique and investigated the effects of passenger motivation on egress through different bulkhead apertures and different passageway configurations leading to Type-III exits [122]. This research demonstrated that high motivation, induced by financial rewards, led to significant ($p<0.01$) differences in performance to that observed under 'normal' experimental motivation levels. This study indicated that findings from experiments using 'normal' motivation levels were likely to be different from those using 'high' motivation levels. It was also found that human factors effects, such as age, gender, evacuation strategy planning were highly influential on the experimental results. In its current from this work has provided useful qualitative data during 'high' motivation conditions. In addition some quantitative information was generated, that could indicate suitable performance decrements that could be applied to simulate 'high' motivation/competitive conditions.

In 1990, Muir et al examined low passenger motivation in theatrical smoke conditions [123]. This work was useful in that it generated further data concerning passenger behaviour under theatrical smoke conditions. This work indicated no significant differences between the Type-III passageway arrangements in smoke conditions (optical density of 0.5 per foot). However, significant differences ($p<0.01$) were noted in the non-competitive trials with and without smoke. From a modelling perspective it provides useful qualitative information on Type-III component performance levels under smoke conditions. It is for example, noteworthy that the configurational impact adjacent to the Type-III exit is less significant in the presence of smoke. Qualitatively, some data exists to validate models of non-competitive smoke evacuations.

Continuing this work, in 1992 Muir analysed the impact of 'high' motivation when evacuating through bulkhead passageways and Type-III exits in smoke with different exit passageway widths [124]. This analysis further revealed that evacuation performance was significantly linked to passageway configurations. In addition, gender was found to significantly ($p<0.05$) effect egress time. However, other human factors such as height, weight and age did not appear to contribute to egress times. In its published form, some of this qualitative data is of use for evacuation modelling in that it provides insight into human behaviour that may need to be represented in evacuation models. For example, in the 13" and 18" passageway configurations, it was suggested that these configurations might have been perceived by the participants as affording more space than actually existed. As a result, multiple passengers attempted to access the passageway simultaneously. This led, on occasions to passengers vying for access to the passageway. From a qualitative perspective, this type of insight into the behaviour of passengers around these type of exit configurations is essential if the correct behavioural response is to be modelled. In addition, some quantitative information was generated regarding the affect of age on egress times. In particular it was shown that the older the participant the longer the egress time through certain passageway configurations. If sufficient data of this type were available to model developers a relationship between age and exiting capability/speed could be developed.

In 1992, McLean et al examined specific dual and triple seating configurations adjacent to single and dual Type-III exits focusing on hatch removal and rates of egress under 'normal' experimental motivation conditions [113]. Again this study revealed significant differences between egress times associated with different exit passageway configurations. This provoked interest in specific passageway arrangements that were explored in more detail in later experiments. Additional information was generated regarding exit hatch removal and disposal times. Evacuation models could use this data to set exit preparation times, i.e. hatch operation time and disposal time, and to better understand the likely effects of various passageway configurations.

Fennell et al investigated Type-III exit configuration in 1993 under 'normal' experimental motivation conditions [125]. This concerned the effects of exit hatch weight and seat configuration on Type-III exit operation and resulting evacuation times. Through the use of anthropomorphic dummies, they also simulated the impact of dead passengers situated immediately adjacent to these exits on evacuation times. They found some differences in exit hatch removal and disposal at specific passageway widths. In addition exit plug weight, passenger gender and passageway configuration were all found to have significant effects ($p<0.001$) on exit opening times. This resulted in numerous findings regarding exit hatch operation and disposal according to gender, age and hatch weight. Indeed in some experiments the weight of the hatch was too great for the operator and the experiments were abandoned. The presence of the anthropomorphic dummy (simulating an incapacitated/dead passenger) revealed useful qualitative data on passenger behaviour. In some cases passengers attempted to move the dummy whereas in other cases they did not. Additional delays in exit operation were incurred on account of the dummies awkwardness and it being located in the out board seat. In its published form, this research has generated useful data for evacuation models on likely human behaviours and some quantitative data on exit opening times.

In 1995, McLean et al published the first of two investigations on evacuation through Type-III exits under 'high' motivation conditions [111]. This study examined seat placement effects on evacuations through the Type-III exits. The primary aim was to provide more definitive answers to the questions raised in previous studies. Indeed the results of this study supported much of the findings of previous work. The effects of passageway widths were again shown to exert significant influences on evacuation performance. The second part of the study examined the effect that individual passenger differences / human factors had upon the experiments [112]. It was found that height did not have a significant impact on egress time but that age, weight, waist size and gender did. Further findings were presented describing effects from a combination of human physical factors. From an evacuation modelling perspective this research is important as it provides qualitative information into the relationship between human physical factors and exiting capabilities. If sufficient data were collected it may provide the basis for establishing the quantitative relationship between these factors and exit capabilities.

In 1996 Muir et al, published additional results from experiments on the 3", 13", 18", 25", 34" and 6" OBR (Out Board seat Removed) exit passageways leading to Type-III exits under 'normal' and 'high' motivation conditions [126]. Again this study found that the Type-III exit passageway width had a significant effect on evacuation efficiency. Learning effects were also noted to influence trial results, highlighting potential problems in comparisons with dissimilar pervious experimental designs. This experiment generated similar qualitative data to previous studies in terms of exit preparation times, the behaviour of passengers using specific passageway configurations and exit flow rates. In addition, some quantitative data concerning exit flow rates for Type-III exits was generated that could be used to calibrate model exit flow rates. It may also be possible to extract from these studies raw data relating to exit hesitation time distributions.

Finally, in 1999 McLean et al, presented results of experiments into the effects of passenger densities (either 30 or 50 passengers) through the 13" Type-III exit passageway [114] with and without cabin crew. For the trials with cabin crew, three different seating locations were investigated. Mclean noted that cabin crew location resulted in insignificant differences in the average egress times. However, the time for the fifth to thirtieth passenger to evacuate through the Type-III exit showed a significant ($p<0.001$) hyper-additive increase in the high-density case and a significant ($p<0.002$) decrease when cabin crew were present. Furthermore, the high-density configuration without cabin crew was by far the slowest case examined. This research has highlighted numerous qualitative factors that could be factored into evacuation models, such as the improved exit flow rates resulting from the presence of cabin crew. However, to be of value quantitative data relating to the impact of crew on exit flow rates should be derived from this experiment. Unfortunately, results from this research are not available in open literature.

These studies represent a huge investment of resource and effort that produced much data on the behaviour of passengers at Type-III exits. Numerous factors were each investigated such as: passageway width, seat encroachment on the Type-III exit aperture, hatch weight, passenger instructions on hatch operation, the method of hatch disposal, the age, weight, height and girth of passengers, the presence of cabin crew, the density of the passenger distribution within the cabin section, etc. Whilst generating much useful data for regulations and the resolution of operational matters, the published results are not always in a form that is of maximum use to evacuation model developers. In order to maximise the benefit for evacuation model development, the video footage from these trials should be made available for further analysis.

It is suggested that future trails should include the involvement of evacuation model specialists to ensure that maximum benefit is derived from such trials and that the data is presented in such a way so as to be of use to model developers. Furthermore, while much work has been done and a considerable amount of data has been collected, before definitive relationships are established for use in computer models it must be established whether or not this data is consistent.

In a recent analysis of this research [114], McLean was forced to conclude that results from these experiments are limited. As McLean stated, the experiments listed above have generally resulted in,

"Data that are largely confounded by individual subject variability and the effects of practice... [and] incomplete designs have often been compounded further by comparisons of the data thusly obtained with other data acquired using similar methodologies, which have, unfortunately, also generally suffered from the same types of deficiencies." [114

In addition to McLean's critique, a recent study by the NTSB concluded that the experiments performed by CAMI that involved Type-III exits contained *"...a number of significant design flaws...that bring into question the applicability of the research to an actual emergency evacuation situation."* [3]. For example, within the CAMI studies that were performed in 1995, each subject performed some 30 evacuations. The NTSB were concerned that significant learning would have occurred over the course of these trials that severely limits the usefulness of these particular studies.

While McLean's confidence in the results of these experiments is low, we have little alternative but to make the best of this data until his reservations are corroborated and more suitable data is made available. Until then, this data is useful in that they have highlighted numerous qualitative trends that evacuation models should include and the quantification of various important human behaviours.

Indeed in a bid to answer some of the questions raised by these studies CAMI have recently completed the most extensive series of aviation evacuation experiments to date

[116,117]. This involved the experimental phase of a new evacuation study of the Type-III exits. This study represents the largest study of these exit types. The experimental phase involved 2544 volunteers split into groups of 55 with each group performing 4 evacuations each, thus producing a total of 10000 exit crossings and 48 naive evacuations.

The purpose of this study was primarily to investigate passageway configuration (6" OBR dual, 20", 13", 10"), hatch location (discarded inside or outside of the exit), subject group density and subject group location. Half of the evacuations used the 'high' motivation technique and half used 'normal' experimental motivation. As each subject performed four evacuations these experiments will be able to analyse the impact of learning. Similar to the CAMI experiments performed in 1995 and 1999, cabin crew marshalled passengers towards the exits from the forward and aft extremities of the cabin. The results of this study are not yet published however they should provide more qualitative and quantitative data for evacuation models.

The results of the research at CAMI and Cranfield University are of interest to evacuation modellers as they identify and quantify numerous relevant factors that influence evacuation. Whilst useful in their own rights, the information is limited as model developers must make use of the data that is published in the format that is published. While addressing important factors, this information may not be in a form suitable for model developers. Ideally, the video records of the experiments should be made available to model developers and model developers should be included in the team designing and analysing experimental results.

Experiments involving Type-I exit performance

Analysis of factors affecting exit performance has not been limited to Type-III exits. Indeed, both Cranfield and CAMI have performed research using Type-I exit types.

As part of the aforementioned Type-III studies, in 1989 Muir et al published the results of experiments into cabin configuration adjacent at exits using the Trident cabin simulator at Cranfield University (Section 2.4.3.1) [122]. These experiments involved 2262 volunteers in groups of 60 taking part in over 134 evacuations of which 80 were through Type-I exits and 54 through Type-III over wing exits. The results of this work indicated that high motivation and low bulkhead aisle widths adjacent to exits were detrimental to evacuation efficiency. This was closely followed by two more studies from Cranfield using the same equipment. The first was in 1990 and examined the effect that theatrical smoke had upon performance under 'normal' experimental motivation conditions [123]. This followed in 1992 by the results of using 'high' motivation techniques [124]. From a modelling perspective, this research has provided quantitative data on the flow rates of passengers through aisles and bulkheads. This data could be used for the validation of model predictions for these aircraft components under 'high' motivation, 'normal' experimental motivation both with and without non-toxic smoke.

In 1996, Muir et al published a report detailing the importance of the number of cabin crew and performance at Type-I exits using the B737 cabin simulator (see Section 2.4.3.1) [127]. In this series of experiments, a total of 1307 volunteers participated in 4 trials in groups of 60. Evacuations, using one active door and two active doors were carried out under 'normal' and 'high' motivation experimental conditions. This research has provided useful qualitative information on influential factors that determine the performance of floor level exits. In addition, this research has provided useful data on the flow rates of exits against which model predictions can be validated.

In 1995 [119] and 1999 [120], McLean et al published the results of a research study investigating the affects of using platforms in place of escape slides during 90-second certification trials. This research was prompted primarily by concern over the validity of recent use of platforms during a 90-second certification trial, e.g. the MD-11 in 1992 [130,131]. Trials of this aircraft were permitted to use slides due to safety concerns following the paralysis of a volunteer during the original certification of the MD-11 in 1991. Whilst the use of platforms had previously been permitted at exits that are not required by FAR to have escape slides, such as over-wing exits on the B737-300, B737-400 and DC-9-80 [90,11,132,133], the use of platforms in place of escape slides was unknown. This research was not just of interest to 90-second certification demonstrations, but also to research in general as previous studies performed at Cranfield had utilised platforms in place of escape slides [122-124,127].

The first study involved a total of 239 adults in groups of 59-60 performing 4 trials each under 'normal' and 'high' motivation experimental conditions and in clear air and smoke. This research concluded that the *"platform allowed much faster evacuations than the inflatable slide"* and that *"doorsill-height platforms do not model escape slides very well"* [119].

The second study investigated the impact the exit size and egress means had on evacuation performance. This study involved a total of 174 volunteers divided into five groups of between 34-36 with each performing six evacuations. The experimental trials involved combinations of 'normal' and 'high' motivation in smoke or clear air onto either platforms or escape slides. The conclusions of this study were that *"...evacuation result obtained with one type of egress means should not be casually generalized [sic] to any other"* [120]. In addition the report stated, *"...evacuations of a specific aircraft should use that aircraft's actual evacuation means to obtain the highest fidelity possible."* [120].

2.4.3.2 Evacuation component testing by manufacturer

In addition to experiments performed at the CAMI/Cranfield facilities, manufacturers frequently test new components of aircraft, such as slides, exit configurations, signage designs, etc. Whilst numerous tests are performed throughout the world the data that they generate is difficult to obtain, as typically it is commercially sensitive and proprietary. However this data if made available could be of great importance to model developers. If the tests are done under appropriate conditions, the data they generate could be useful for both 90-second certification trial scenarios and real accident analysis. A further discussion of these tests and the role they can have in modelling for certification can be found in Section 2.4.1.

2.4.3.3 Thermo-toxic environments

Present in many real emergencies is a thermal and toxic hazard that is capable of hindering evacuation and/or causing loss of life. As such, evacuation models that attempt to simulate real emergency evacuations require a representation of both the affects that they have upon passenger behaviour and the possible loss of consciousness and ultimately life. The FAA has been investigating the effects of pooled fires on aircraft cabins and its toxicological impact upon passengers for many years. Their work and its appropriateness for the purposes of evacuation modelling is summarised in this section.

Firstly, it is necessary to define the principle type of fires that are likely in an emergency aircraft evacuation. Fires may take the form of internal fires, possibly originating from damaged or defective aircraft systems, or an external pooled kerosene fire. The majority of research by the FAA has been focused on the external pooled kerosene scenario.

The FAA C133 full-size fire test facility

The FAA C133 fire test facility subjected a mock aircraft cabin to a pooled kerosene fire. The pooled fire originated from an external tray measuring 10 feet by 8 feet which contained 50 US Gallons of kerosene fuel and was positioned at the sill height of a Type-A sized exit opening. The size of the opening was supposed to be representative of a rupture in the cabin fuselage, thus passenger seating was situated directly adjacent to the Type-A sized opening.

The size of the tray was determined through tests of various tray sizes in order to reproduce the radiant flux of an "infinitely" large pooled kerosene fire [82]. The data for an "infinitely" large pooled fire was obtained through subjecting a real DC-7 aircraft [135] to an external pool fire of 30 feet in diameter through a similar sized opening. The resulting radiant flux when measured at the centre line of the cabin fuselage during the DC-7 test was only marginally higher (20%) than the radiant heat flux from the C133 fire test model.

The result of their experiments was that their test aircraft cabin section consistently flashed over at approximately 2¼ minutes. This finding was explicitly stated by the FAA technical report:

"Uncontrolled post-crash fires in an intact fuselage will produce flashover condition, which will be followed by a loss in survivability throughout the cabin." [82]

In a bid to ascertain the validity of the C133 test model's findings, Trimble [134] reviewed 10 aircraft accidents with fires, for the occurrences of flashover, smoke and/or gas induced debilitation/collapse before completing egress and he also examined the time-scale of the evacuations. The cases Trimble investigated are summarised below:

- United Airlines DC-8 at Denver on 11.7.1961
- United Airlines Boeing 727 at Salt Lake City on 11.11.1965
- Varig Boeing 707 near Paris Orly on 11.7.1973
- Saudi Arabian Airlines L1011 at Riyadh on 19.8.1980
- Spantax DC-10 at Malaga on 13.9.1980
- Air Canada DC-9 at Cincinnati on 2.6.1983
- Pacific Western Airlines Boeing 737 at Calgary on 22.3.1984
- British Airtours Boeing 737 at Manchester 22.8.1985
- Delta Airlines Boeing 727 at Dallas on 31.8.1988
- US Air Boeing 737 at Los Angeles on 31.8.1988

With respect to flashover, Trimble found that in two of the cases (6 and 8) flashover was completely discounted by their air accident investigations. The remaining 8 cases investigated had no mention of flashover although smaller flash-fires were mentioned in some air accident reports. His analysis of gas induced debilitation collapse revealed that for the majority of passengers incapacitation occurred as a result toxic gas inhalation. Additionally, Trimble found that an average evacuation time-scale from 9 accidents was 3 minutes and 50 seconds.

Trimble's conclusions were that, whilst the FAA C133 test model certainly does represent an aircraft fire scenario, the test model should not be assumed as the general pattern for real aircraft pooled fire scenarios [134]. Indeed, Trimble argues that the testimonies of passengers and the pathological evidence from real aircraft accidents indicates that toxic gases are the principle source of incapacitation not excessive exposure to thermal radiation, as indicated by the C133 test model. As such, Trimble questions the validity of extrapolating from the test model to real aircraft fires. As Trimble stated during his Thesis:

"The C133 fire test model results from the FAA technical centre, that there is no significant threat to occupants from combustion smoke and associated toxic/irritant gases before flashover occurs in an aircraft cabin. Such a view does not accord with the testimonies of many survivors from previous fire related accidents, nor the

associated toxicology, and it is considered that there is sufficient discrepancies between the results from this particular fire test model and real accident experience to indicate that the apparent findings from this fire model and the above premise have been relied upon to an unwarranted degree." [134, pp110]

From an evacuation modelling perspective the results of these tests provide some useful data on a possible thermo-toxic scenario during a real emergency evacuation. In addition these experiments have been useful in highlighting and quantifying the types of gases that are released from the pyrolysis of an aircraft cabin and its furnishings. Using these data, evacuation models can be configured to represent the experimental fire. However, the data generated from these test fires cannot be assumed to be the only or most representative fire scenario for aircraft accidents. Indeed, according to the work of Trimble, the toxic data generated in these test fires is unrepresentative of the most challenging aircraft fires that occur.

Computer based methods of modelling fire

In addition to using data from fire tests, computer fire models can be used to generate the fire atmosphere that passengers are subjected to. Computer models to simulate fire are generally categorised as being either Zone [83] or Computational Field Dynamics (CFD) [87] based. Zone models generate an average heat, gas and smoke concentration for both upper and lower layers in each zone with the output for each zone being an average. CFD based models subdivide each compartment or zone into thousands of small three-dimensional cells. The physical properties, i.e. gas, heat and smoke concentrations are then calculated for each cell. As finer meshes are employed within CFD models, they can more accurately predict velocity and temperature fields. Whilst generating more detailed results the approach is computationally expensive. With respect to simulating fire spread through an aircraft cabin, the size of the mesh elements is of importance, as it would affect the results of the model. Of the two approaches, CFD would generate the most accurate results however at relatively high computational expense.

Human tolerance to thermal and toxic hazards

Much research has been carried out to ascertain human tolerances to thermal and toxic hazards. This research has primarily been performed using rats, mice and monkeys as human surrogates [136-145]. The toxic gases that required investigations have been determined through the pyrolysis of aircraft cabins and furnishings as well as through the pathological analysis of accident victims [134,81,82,99]. Thus, human tolerance experiments have analysed tolerance to specific toxic products and toxic combinations [136-145].

The concept of Fractional Effective Dose (FED) has been utilised to model the time taken to incapacitation from various different toxic threats, such as Heat, Radiation, Hydrogen Cyanide (HCN), Hydrogen Fluoride (HF), Hydrogen Chloride (HCl), Carbon Dioxide (CO_2) and Carbon Monoxide (CO). The FED is numerical and is therefore ideally suited to computer models. The FED model has been described numerous times previously [88,89], and so will not be described in detail here. Suffice to say that the FED assumes the effects of its components to be additive and is reliant upon having good quality data when specifying its parameters. Originally the FED model was only able to indicate the time to incapacitation from asphyxiant gases.

The effects of asphyxiant gases are that, in sufficient quantities they affect ones ability to breath and to remain conscious. As Purser states they *"affect the nervous and cardiovascular systems, causing confusion followed by loss of consciousness, followed ultimately by death from asphyxiation"* [89]. Common asphyxiant fire gases include CO, HCN, CO_2 and (low) O_2 [89]. A common exposure profile is that *"There is little effect initially, but when a critical threshold dose level is reached severe effects occur suddenly. These consist of a brief period of intoxication (similar to severe alcohol intoxication), followed by a collapse into unconsciousness."* [89].

Later, Purser expanded the FED model to include the effects of irritants [89]. Irritants are not just highly irritant but also potentially depilating gases, such as HCl, HF, Sulphur Dioxide (SO_2), Nitrous Oxides (NO_x) and Acrolein (HCHO), that are nearly always present in aircraft fires [134,89]. In sufficient quantities these irritant gases can cause severe discomfort and agitation, such that passenger's ability to escape is annihilated to *"a degree of incapacitation approximately equivalent at the point of collapse resulting from exposure to asphyxiant gas"* [89]. Even in small quantities irritant gases can cause *"Painful stimulation of the eyes, nose, throat and lungs"* [89]. However, Purser recognises that quantifying their effects for any one individual is difficult as *"Effects lie on a continuum from mild eye irritation to severe eye and respiratory tract pains"* [89].

The net result of this research is an empirically based mathematical model of human tolerances to toxic and thermal assault. The FED model not only models time to incapacitation but also time to irritation. Furthermore, being numerical, the model is ideally suited to integration into computer evacuation models. However, like any model, it is only as good as the data upon which it is based.

Human behaviour in smoke

In recent years, human behaviour experiments in smoke have been limited to non-irritant toxic theatrical smoke [128, 124]. Experiments in aircraft have been conducted both at Cranfield [123,124] and CAMI [109,110]. However, some years ago, experiments were performed using irritant smoke and human volunteers [146,81] in non-aircraft enclosures [146].

The primary impact of smoke is that particulate in the atmosphere obscures the amount of light that is transmitted, thus leading to a decreases in visibility. During an emergency evacuation this has the effect of limiting passenger visibility creating disorientation. In addition, passenger movement is also affected. Passengers may decide to crawl so as to avoid contact with the upper hot and dark smoke layer. In very dense smoke, passenger vision is completely annihilated and positional awareness is limited to tactile information.

The FAA conducted some tests into the effects of smoke on cabin visibility [81,149,150]. In these experiments passengers were required to read letters signs through various concentrations of smoke. The effects of cabin and sign luminescence, and letter spacing were examined using white [149] and black smoke [150]. Passengers were not subjected directly to the smoke in these experiments. However, in earlier experiments this had been shown that the ability to read signs was reduced in irritant smoke conditions when compared against non-irritant conditions. This was attributed to discomfort and eye lacrymation. Similar affects have been reported in real aircraft accidents [10].

Jin subjected volunteers to irritant and non-irritant smoke whilst performing a complex action and walking through a corridor [146]. In this work, Jin showed that human performance both in terms of movement ability and performing their task were reduced in irritant smoke.

The results of this research are that it is possible for computer models to have some representation of human behaviour in smoke environments. However, the work of Jin was performed in a corridor not an aircraft cabin. Consequently it is not of direct relevance to behaviour in aircraft, as it is likely that a different range of behaviours would be exhibited when moving through smoke within an aircraft cabin. As such more research is needed in order to better understand the behaviour during smoke environments. Ideally, video footage of subsequent trials involving smoke would be made publicly available for the benefit of evacuation modellers. Furthermore, the work that has been done in aircraft enclosures [123,124] have not controlled or quantified the concentration of smoke the passengers have been subjected to. It is not possible to determine the impact of smoke concentration on human performance in these experiments and therefore it would be desirable to conduct a range of experiments within aircraft environments in which the smoke concentration was controlled.

2.5 Concluding remarks

This chapter has provided the answer to the question "Are there currently evacuation models appropriate for certification and accident applications. If so what are they and what are they lacking?" In doing so all six of the aviation evacuation models that have been developed to date were described. Of these only one (airEXODUS) is still being funded and developed.

A main critisicm of evacuation models was that most failed to use empirical data to determine model parameters. Indeed, of the six models that were found only GPSS and airEXODUS use real evacuation data within their models. The complexity and completeness of each of the models behavioural sets were discussed in detail. In this context airEXODUS and AIREVAC contained the most complete set of human behaviours. It should be noted that whilst modelling many of the common behaviours found in evacuation the parameters used in AIREVAC were completely arbirary. Finally, whilst most models' validation studies have been positive, in general the validation history of aviation evacuation models is rather limited. 90-second certification trials offer an available and abundant source of data against which evacuation models could be validated. These should be utilised in future model development. A further finding of this chapter is the importance of experimental data and data from real accidents in understanding and specifying behaviours within evacuation models. In this respect the AASK database offers a wealth of information on human behaviour in real aircraft accidents. This tool makes it an ideal source for the a) verification and b) development of future, behaviours in evacuation models.

3 An overview of the airEXODUS V3.0 evacuation model

3.1 Introduction

The primary aim of this thesis is to advance aircraft evacuation modelling technology towards viable tools for use in the certification and design of passenger aircraft. One method of achieving this would be to code an entirely new model and validate it to a sufficient level to meet the objectives. However, given that current aircraft evacuation modelling technology has already reached a certain level of maturity this approach would waste valuable time that could be devoted to extending an existing model. Thus, the approach taken by this thesis is to develop an existing aircraft evacuation modelling platform.

The previous chapter provided and discussed the history and methodologies behind evacuation modelling and the research and data that are available to them. From those discussed it is apparent that the airEXODUS evacuation model sits at the forefront of evacuation modelling technology and is therefore an ideal platform for this thesis. This chapter provides a detailed view of its current mechanics and capabilities and helps to explain what the airEXODUS model – and aircraft evacuation modelling technology - is lacking.

3.2 *Model overview*

Detailed literature describing the airEXODUS model is available in the public domain and so it will not be exhaustively discussed in this thesis [36-38,40-52]. However, an overview and understanding of the current state of airEXODUS development will be presented. This section is based on airEXODUS V3.0 functionality.

airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90 second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

EXODUS comprises five core interacting sub-models (see Figure 5) they are the Passenger, Movement, Behaviour, Toxicity and Hazard models.

The software describing these sub-models is rule-based, with the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The simulation clock increments at 1/12 second intervals.

3.3 The geometry sub-model: Spatial definition with airEXODUS

Within airEXODUS the aircraft geometry is divided into a series of discrete spaces referred to as nodes connected by a series of arcs. An arc connection between two nodes defines a travel path between the two nodes. The connection of a nodal mesh in such a manner enables complex geometries to be specified within the model (see Figure 12 and Figure 13).

A node represents a region of space that has dimensions of 0.5 metres by 0.5 metres. Within the model, dimensions are represented via setting the length of non-diagonal connecting arcs to 0.5 metres and diagonal arcs to 0.707 metres. In practice these dimensions are rarely used as the constricted geometry of passenger aircraft requires smaller or occasionally larger node sizes. For example, an exit passageway with a width of 0.95 metres would be modelled with two nodes with a width of 0.425 metres.

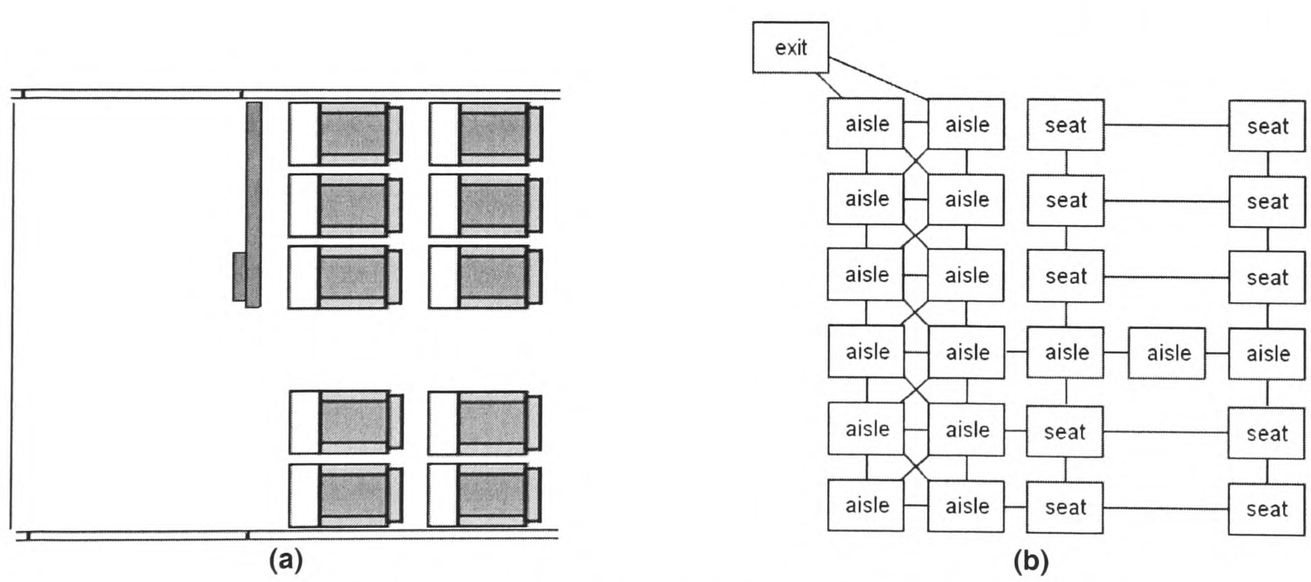


Figure 12: Example representation of a forward cabin section

Within aisles the size of nodes is typically set differently to reflect a) the orientation of the passengers' body and b) observations from 90-second certification trials in which two passengers can occupy the length of a seat when in the aisle. The general method when defining space in aisles is for two aisle nodes to be provided per passenger seat. The front aisle node being connected to the passenger seat (see Figure 12(b)).

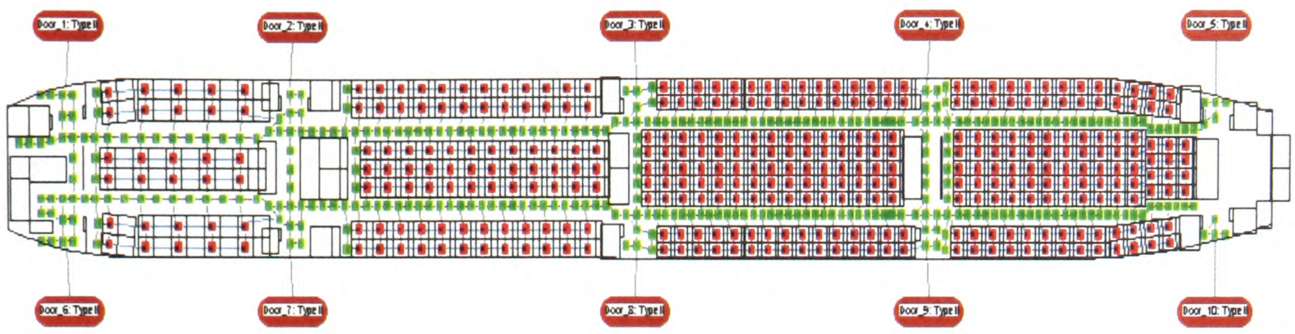


Figure 13: Cabin layout in airEXODUS. View depicted represents the interactive graphics component within airEXODUS. Aircraft depicted has five pairs of exits. The node structure showing seats, aisles and cross-aisles is clearly depicted.

3.3.1 Node attributes

Each node has a set of attributes defining its terrain type and environmental state. Within airEXODUS nodes are assigned types reflecting different terrain. Terrain types are AISLEs, SEATs, EXITs and STAIRs. The terrain type affects the movement speed of passenger when traversing the node. Likewise arcs can be assigned obstacle values to reflect the obstacle over a specific path. The obstacle value of arcs affects both travel speed and may also require a certain amount of agility for the passenger to travel the arc. Through arc obstacle values the relative ease of lateral movement through seating is modelled via low arc obstacle values whereas longitudinal movement over seat backs is modelled with high arc obstacle values.

Table 5: Movement rates according to terrain type

Terrain Type	Movement speed
Aisle	Fast walk
Seat	Walk
Boundary	Walk
Stair	Individual stair up/down
Exit	Fast walk

Environmental attributes include the, concentration of HCN (ppm), CO (ppm), CO_2 (%), oxygen depletion (%), smoke (l/m) and temperature (^oC). For each of these variables, two values are stored, representing the value at head height (1.7m) and near floor level (0.5m). In addition each node is assigned a potential value which is explained in more detail later.

3.4 The movement sub-model within airEXODUS

Within airEXODUS movement is generally determined via the potential values of nodes calculated through a potential map also known as a potential well. The potential map is a mechanism by which the relative merit of each node is determined and is calculated according to the attractiveness of each door as supplied by the user. Prior to simulation it is necessary for the user to supply potential values to each exit – the values represent the attractiveness of the exit. airEXODUS then increments the potential value and assigns it to all adjacent nodes. This process is repeated until there are no more adjacent nodes (see Figure 14(a)). Should more than one exit be active the process is repeated assigning nodes the lowest potential value for each exit (see Figure 14(b)).

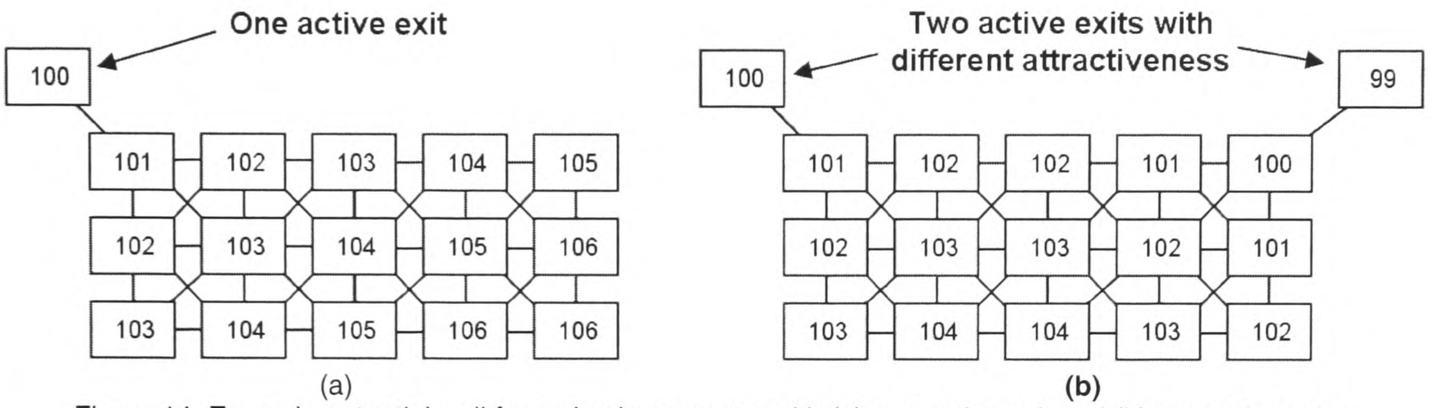


Figure 14: Example potential well for a simple geometry with (a) one active exit and (b) two active exits

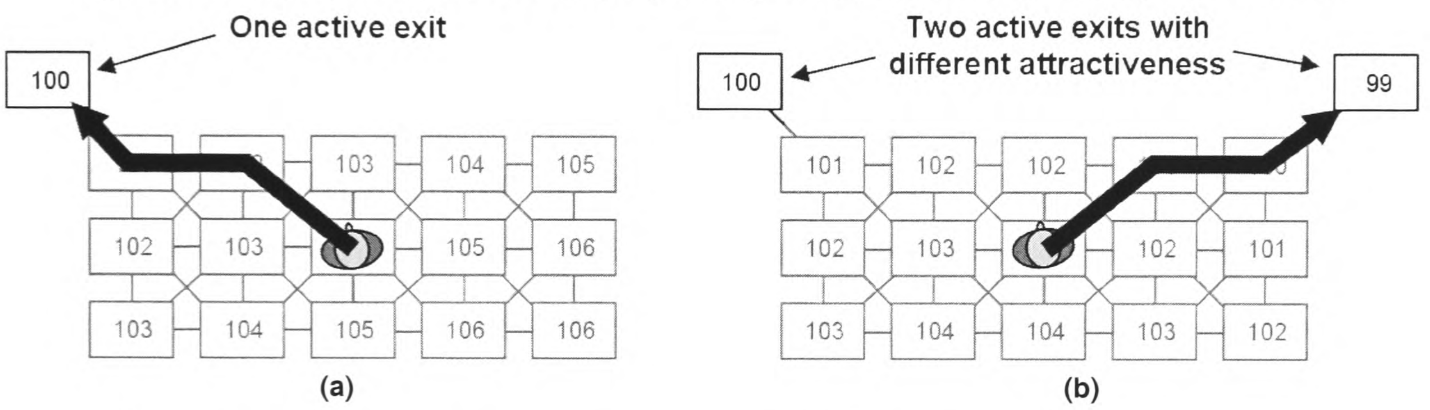


Figure 15: Movement of a passenger with (a) one active exit and (b) two active exits

Using this method nodes are assigned increasingly higher potential values representing their distance, as measured by nodes, from the exit. Within the model passenger movement is simplistically determined via seeking nodes with lower potential scores than the current node. Should all lower nodes be occupied passengers may choose nodes with equal potential values. Furthermore, when a passenger has been waiting on a node for a length of time that is greater than their patience attribute they may move to nodes with increased potential values until a node of lower or equal potential is found. Using this scheme when two active exits are available the exit choice of passengers' is simplistically determined by the number of nodes that lie between the passenger and the exit and the initial potential values of the exits (see Figure 14(b)).

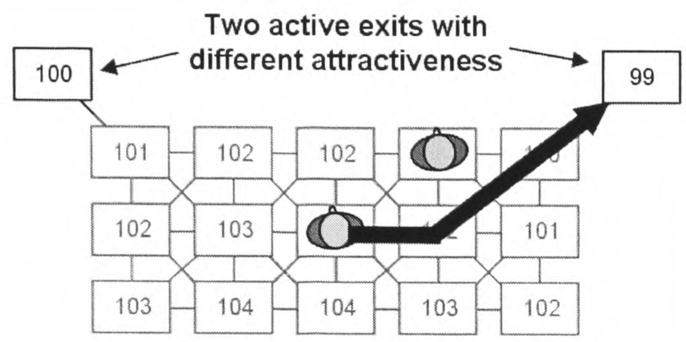


Figure 16: Revised movement pattern avoiding another passenger

This mechanism alone is unable to generate the required movement pattern in complex aircraft geometries especially those involving cross aisles. To remedy this ATTRACTOR/DISCHARGE nodes are used within the model. These special node types allow the user to impose specific potential values on nodes. The value at the attractor is used as the seed potential for adjacent nodes except for discharge nodes, which are used to segregate areas to be effected.

An example application of attractor / discharge to a hypothetical cabin section is shown in Figure 17. In Figure 17 only the top left door is active therefore the potential map would be generated for the cabin as shown in Figure 17(a) and (b). This does not reflect a likely movement pattern as passengers may in reality choose to use the cross-aisle rather than cutting through seating. Thus, two sets of attractor/discharge nodes are deployed (see Figure 17(c)) and would alter the potential map accordingly. It can be seen that the use of attractors generates the desired behaviour and passengers would use the cross-aisle rather than cutting through the seating (see Figure 17(d)).

When used for the redirection of individuals to specific exits the standard potential well system and use of attractor/discharge nodes was found to be too cumbersome to allow some of the more complex movement patterns that were required in later chapters of this work. Thus, some small but significant modifications to the standard potential well system as deployed in V3.0 of the software were made. Whilst inappropriate to mention in this section the alterations are relevant to some of the later model developments in this thesis. As such they have been included as Appendix B.

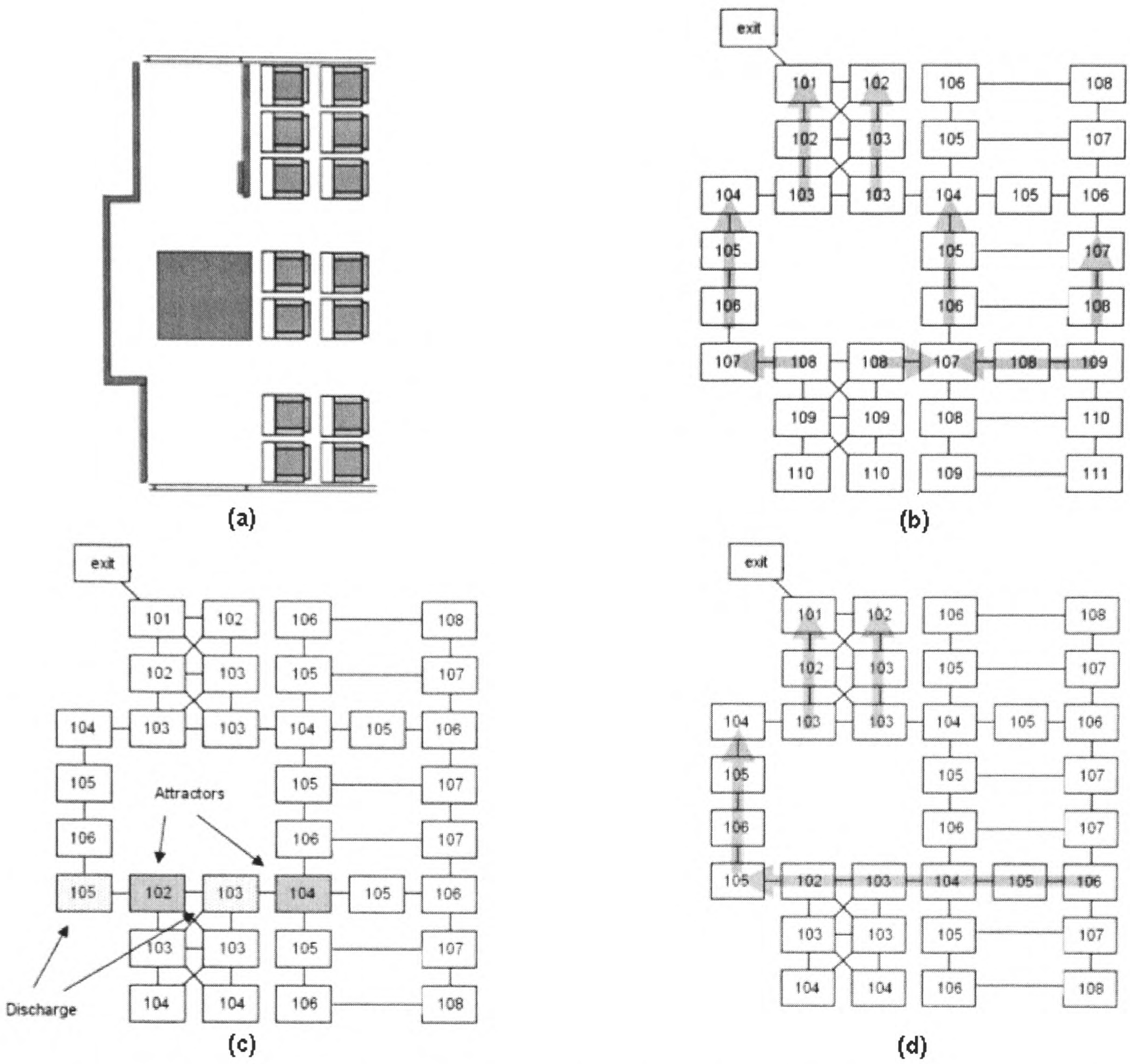


Figure 17: Example application of ATTRACTOR/DISCHARGE nodes within the model

3.5 The hazard sub-model

Within airEXODUS fire hazards can be defined to act over one or more nodes during one or more time periods during the evacuation. Within airEXODUS a hazard consists of growth equations for O, CO, CO2, HCN, Smoke, Radiative Flux and Temperature. Many hazards can be defined for each node within the model although only one hazard can affect a node at any given time. Within the model large transformations in ambient conditions are modelled through two or more hazards that affect the node(s) at different times during the simulation.

Hazards can be specified by the user in the form of growth equations or generated automatically from CFAST [84]. User specified growth equations require manual input although the equations could be derived from experiments, research or hypothetical data. Automatic faculties are provided to allow the direct import of data from CFAST.

When CFAST is employed the nodes that the hazard affects has to directly correspond to the compartments within the zone model.

3.6 The toxicity Sub-model

3.6.1 Physiological attributes for the FED model

airEXODUS makes uses of the fractional effective dose model for determining the affects of hazards upon passengers. As such it is necessary to record individual measures of toxic exposure and its cumulative effects. Within airEXODUS the following individual physiological parameters are used: PID, FIH, FICN, FIO, VCO2 and FIN. The personal incapacitation dose (PID) is a measure of the carboxyhaemoglobin (COHb) concentration necessary to cause incapacitation as determined via the FED model. FICO measures the passenger's cumulative exposure to carbon monoxide (CO). FICN attribute measures the passenger's cumulative exposure to hydrogen cyanide (HCN). The FIO attribute measures the passenger's cumulative exposure to low oxygen (O_2). VCO2 attribute is an estimate of the hyperventilation effect caused by the passenger's exposure to carbon dioxide gas (CO_2). The FIN attribute measures the passenger's combined cumulative exposure to low O_2, HCN, CO and CO_2.

Within EXODUS Pursur's FED [16-19] is utilised which estimates the time to incapacitation and considers the physical and toxic hazards associated with HCN, CO, CO_2, elevated temperature and low O_2.

In each of the following expressions, t is the exposure time (minutes). The fractional incapacitating dose (FID) for each of the agents is calculated as follows:

CO (measured in ppm):

$$FICO = 3.317 * 10^{-5} * CO^{1.036} * RMV * \frac{t}{PID} \qquad 1$$

where RMV is the Respiratory Minute Volume (litres/minute) and PID is the Personal Incapacitation Dose (%). Equation 1 is however unreliable for small adults and children and that CO is immediately converted to COHb.

(ii) HCN (measured in ppm):

$$FICN = e^{(\frac{HCN}{43})} * \frac{t}{220} \qquad 2$$

Equation 2 is however is unreliable outside the range 80 - 180 ppm HCN.

(iii) Low O_2 (measured in %):

$$FIO = \frac{t}{e^{(8.13-0.54*(20.9-O_2))}} \qquad 3$$

(iv) CO_2 (measured in %):

$$FICO_2 = \frac{t}{e^{(6.1623-0.5189*CO_2)}} \qquad 4$$

Another effect that CO_2 has is to increase an exposed person's RMV and thus increase their rate of uptake of other toxic gases.

The FED model considers the combined effect of these agents in the following way,

$$FIN = (FICO + FICN) * VCO_2 + FIO \qquad 5$$

where,

$$VCO_2 = e^{(CO_2/5.0)} \qquad 6$$

is a multiplicative factor which measures the increased uptake of CO and HCN due to CO_2- induced hyperventilation.

The final hazard considered is due to heat. There are two contributions to this relationship, convective heat (i.e. elevated temperature) and radiative flux,

(v) Convected Heat:

$$FIH_C = t * 2.0 * 10^{-8} * T^{3.4} \qquad 7$$

where T is the temperature (°C).

(i) Radiative Heat:

$$FIHr = \frac{q^{1.33}}{D_r} * t * 60.0 \qquad 8$$

where q is the radiative flux (kW/m^2) and D_r is the radiative denominator. D_r is the Dose of radiation required to cause the desired effect and has units of [s(kW/m^2)$^{4/3}$]. Within EXODUS two values for D_r are provided, these represent the critical value for "pain threshold" D_r = 80 and the critical value for "incapacitation", D_r = 1000. Both values are subjective and depend on many variables such as age of the passenger, state of health, amount and type of clothing worn, amount of skin exposed etc. As a result these values are only intended to be indicative.

The FED model considers the combined effect of these agents in the following way,

$$FIH = FIH_r + FIH_c \qquad 9$$

When FIN or $FICO_2$ or FIH equal or exceed 1.0, the affected passenger is assumed to be incapacitated. The EXODUS model considers fire hazard data located at two heights, head and near floor height.

While the Purser model is typical of FED models, other formulations have been suggested, Speitel [26,27] for example has developed an alternative model. In addition to the quantities specified in the Purser model, Speitel considers the gases, HCL, HF, HBr, Acrolein and NO_2. Furthermore, expressions for the CO and Heat contribution to the FED calculation are significantly different from that specified in the Purser model.

In Pursers model the FIH_C acquired each minute (equation 7) is based on data using subjects with exposed skin, whereas in the Speitel model the FIH calculation, is based on data using clothed subjects.

$$FIH_C = t * 2.4 * 10^{-09} * (T°C)^{3.61} \qquad 10$$

The Purser model predicts incapacitation at significantly lower temperatures than the Speitel model. For example, according to equation 7, a one-minute exposure to 185°C results in incapacitation, whereas using equation 10 temperatures in excess of 240°C are required to produce the same result. A possible deficiency in both models concerns the exclusion of the thermal effects due to humid rather than dry air. The incapacitating effects of air with a high water vapour content are more severe than dry air as it reduces heat loss through sweat and delivers more heat to exposed skin. Furthermore, due to its higher heat capacity, inhaled hot air with a high water vapour content can cause more severe damage to the respiratory tract than dry air at the same temperature [23].

Both the Purser and Speitel models incorporate a factor that takes into account the increased respiration rate that results from the presence of CO_2. The hyperventilation factor, VCO_2 (see equation 8), is used in the Purser model to represent the increase in uptake of CO and HCN and in the Speitel model it serves a similar function for CO, HCN, HCL, HF, HBr, NO_2 and Acrolein. Using equation 8, a 5% atmosphere of CO_2 will increase the RMV by a factor of 2.72. This will have a significant effect on the FIN calculation in both models.

The final parameters which can be accessed through the toxicity submodel are called the TRIGGERING TEMPERATURE and TRIGGERING SMOKE CONCENTRATION. These parameters apply to the entire population. They represent the critical temperature and smoke concentrations at which a passenger's response time attribute is overridden.

3.7 The passenger sub-model

Within airEXODUS passengers each have individual defining characteristics that are typically determined according to age/gender/weight from various empirical source and experimental sources. Generally, attributes can be categorised as being physical, psychological and physiological.

3.7.1 Physical attributes

These attributes cover the physical characteristics of the passengers of which some are fixed and others change throughout the evacuation. Fixed physical attributes within airEXODUS are gender, age, weight, maximum travel speeds, maximum agility and normal RMV. In addition six travel speeds are provided in airEXODUS to represent different modes of travel and speed over various terrain/obstacles. Travel speeds are: crawling, climbing seating, running, walking and climbing/descending stairs. The travel speed is determined by the terrain that is being traversed and the action being undertaken. Normal RMV is determined according to weight, gender and age.

Current agility and travel speeds are dynamic attributes that are affected by a mobility attribute which is determined according to the condition of the individual. Toxic gases, high/low CO/O and injury all affect passenger mobility which in turn impacts upon passengers' agility and travel speeds. RMV is affected by the level of work, i.e. the travel speed and the action being performed.

The narcotic affects of smoke and narcotic gases affect passenger mobility. The impact that smoke has upon mobility is determined via the work of Jin [146] (see Figure 18 and Table 6 and Table 7). Where FIN and smoke combine to reduce mobility the greater factor is assumed.

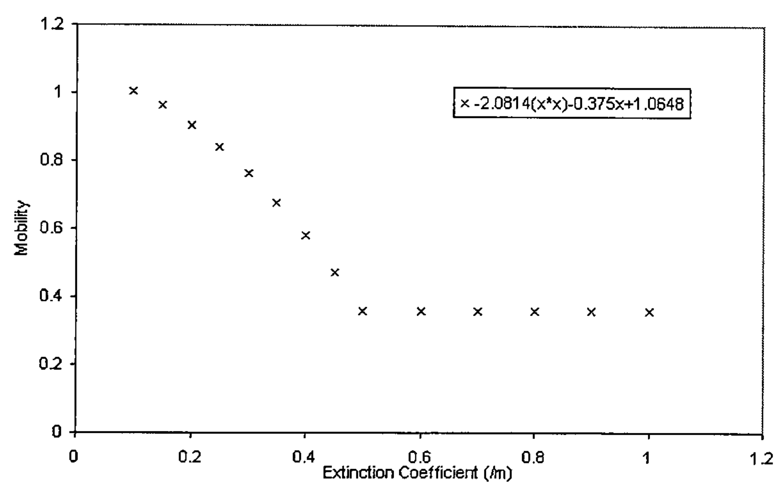


Figure 18: The impact of smoke upon occupant mobility derived from the work of Jin [146]

Table 6: Relationship between smoke and mobility derived from the work of Jin [146]

Smoke Concentration (1/m)	Mobility
0.0 - 0.1	1.0
0.2	0.92
0.3	0.76
0.4	0.57
0.5	0.36
>0.5	0.36 + Crawl

Table 7: Relationship between FIN and occupant Mobility attribute

FIN	Mobility
0.00 - 0.89	1.00
0.90 - 0.95	0.90
0.96 - 1.00	0.80

3.7.2 Psychological attributes

In addition to physical attributes some psychological attributes are provided that are used in determining the passenger's response to situations. In airEXODUS V3.0 three psychological attributes are used: Drive, Patience and Response Time.

Drive is used to resolve conflicts for space and is determined according to gender and age as indicated by competitive evacuation trials involving financial payments to evacuees who are amongst the first few to successfully evacuate [22,23]. Patience is a measure of how likely the passenger is to wait in a queue rather than to seek a method of circumventing the queue, through extreme behaviour.

The response time attribute reflects the time required to recognise the need to evacuate, unbuckle seat belts and stand. This attribute represents the psychological responses to the alarm as well as the physical unbuckling seat belts and standing actions. These values were determined from previous analysis of 90-second certification trials and are set according to gender and age.

3.7.3 Crew attributes

Crew share the above attributes but are provided with an additional task list of actions that they have to perform. In airEXODUS V3.0 tasks are rather limited and cover simple behaviour such as, move to a location, wait at a location, open/close a door and check whether catchment area of an exit is empty. Crew can be assigned any number of tasks and complete them sequentially.

3.8 The behaviour sub-model

The global behavioural pattern has already been described (see Section 3.4) and involves passengers following the potential well to the exit with the lowest potential. Within airEXODUS another layer of behaviour exists called, Local Behaviour.

Local behaviour covers, A) people-people interactions, B) environmental affects, and C) terrain movement adjustments. These behaviours are strongly affected by the individual characteristics of passengers and the scenario in which they are present.

Generally passenger behaviour is categorised as being either EXTREME or NORMAL. Normal behaviour sees passengers follow the potential map in an orderly manner. Extreme behaviour is activated when passengers' exceed their patience threshold. Extreme behaviour allows passengers to occupy nodes with higher potential values than their current node. In addition and agility permitting, passengers may travel over seating when in EXTREME mode. Passengers may sometimes leave an aisle and then climb over seating in this mode of behaviour. In this instance the behaviour results from two rules A) being allowed to increase their potential and thus move away from the aisle, and then B) climb over seating, i.e. occupy the node with the lowest potential excluding the previous node.

Within the model passengers are forbidden to move into EXTREME mode when they are within close proximity to an active exit, usually set to 2 metres within the model. This override stops passengers from moving away from an active exit due to temporary obstructions or blockages.

Conflicts for space are resolved using the Drive attribute of each passenger. Where more than one passenger vies for the same node, the Drive attributes are consulted with the passenger with the higher Drive winning the conflict. Specific time penalties are attached to winning and losing conflicts. Reduced travel speeds during periods of congestion emerge from the frequency of conflicts that are generated.

Direction changes generally occur when new exits become available and the potential well is recalculated. Over taking behaviour is implicit in the potential well movement system. The terrain that is being traversed also affects the current movement speeds of the passenger.

Finally, airEXODUS contains limited environmental behaviour effects. If the upper hazard layer reaches excessive levels of smoke or heat passengers begin to crawl so as to avoid contacting the hazard. This affects their movement speed. In addition toxicological affects as calculated via the FED model affect passenger travel speeds, mobility and consequently agility.

It is apparent from this description that passengers have no knowledge of the exit that they are going to use within airEXODUS and merely know the next best node to occupy. In essence passenger movement is determined solely on a local basis, with passenger essentially looking at their feet as they walk.

3.9 Certification data used in airEXODUS

airEXODUS makes use of 90-second certification data [158] to specify certain model parameters [46]. In the work presented here, the most important parameter is the Passenger Exit Delay Time. This time represents two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit.

In general, the exit hesitation time is due in main to passengers either waiting at the exit for the path to clear and/or contemplating how to negotiate the exit. In either case, the exit negotiation stage does not usually start until there is space for it to commence. Furthermore, the process of passing through the exit and travelling from the exit to the ground are considered as separate events that can occur in parallel.

Within airEXODUS the exit delay time distribution is segmented into subintervals described by uniform distributions. The technique is dependent on the user having a good representation of the actual delay time distribution. This representation used within airEXODUS is discussed in more detail later.

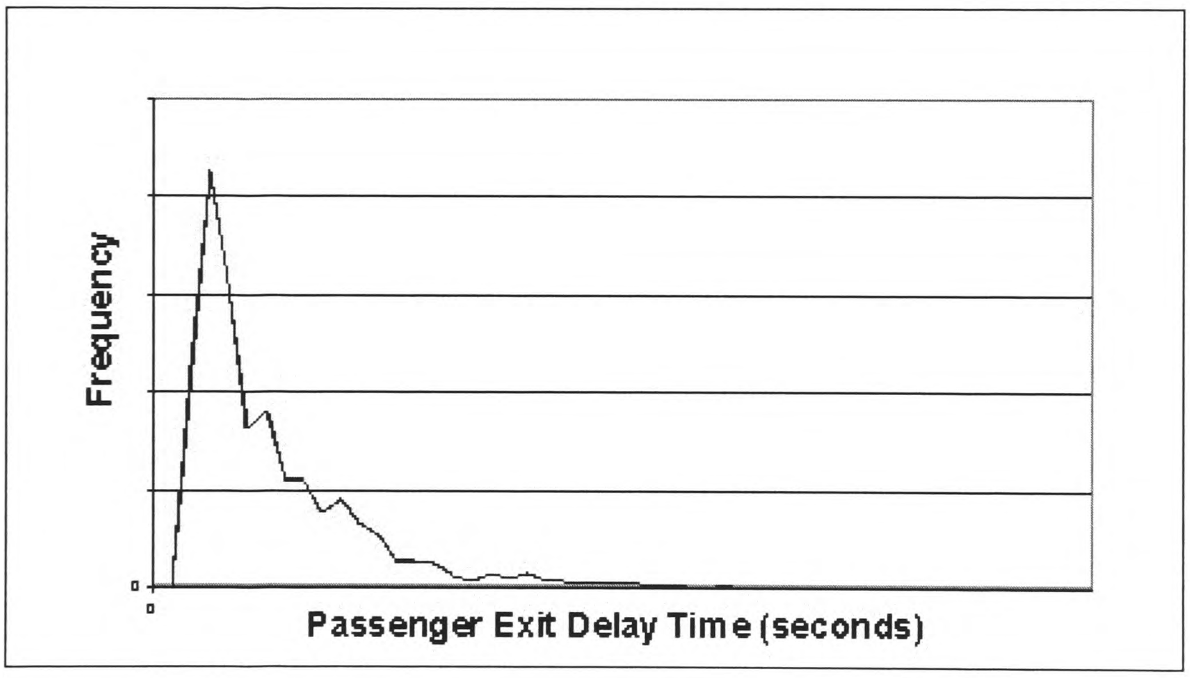


Figure 19: Passenger Exit Delay Time distribution for main deck Type-A exits with assertive crew.

The main deck Type-A exits (a description of the different type of aircraft exits may be found in Appendix A) with assertive cabin crew serves as a typical example of the analysis that has been conducted on passenger behaviour at exits. For this exit, assertive cabin crew were taken to be crew who displayed a vocal and physical assertiveness during the majority of the passenger flow through their exit. Vocal assertiveness is taken to mean crew members who continuously yelled clear instructions to the passengers and physical assertiveness is represented by crew members who made physical contact with the passengers.

From the FSEG analysis, suitable data from 11 previous certification tests involving Type-A exits with assertive cabin crew were found. The aircraft meeting these selection requirements were drawn from Boeing, Airbus and Douglas aircraft. It is also worth noting that three of these aircraft failed to meet the FAR part 25.803 certification requirements. In total, passenger exit delay time data from 20 exits representing some 2078 passengers were used to determine the passenger exit distribution. For each exit meeting the selection criteria (i.e. Type-A, main deck, assertive crew) a frequency distribution curve of passenger exit delay time can be generated. The shape of these distributions are remarkably similar, resembling an exponential/Poisson distribution that peaks at the low end of the delay time distribution and tails off towards the higher end of the distribution. This suggests that the majority of the passengers display a short delay time (associated with a rapid jump onto the slide) while a sizeable number of passengers have a relatively long delay time (associated with passengers that sit on the exit sill when using escape slides). On the whole, the slowest passengers exit delay times are associated with personal attributes of being elderly and being female. From this data we note that the minimum delay time is approximately 0.2 seconds and the maximum delay time is 4.7 seconds. The typical distribution of delay times for main deck Type-A exits with assertive crew is depicted in Figure 19. The shape of the curve for unassertive crew is similar to that shown in Figure 19 with the fastest times being unaffected but with more passengers displaying the slower times.

For each exit type, generalised passenger Exit Delay Time distributions have been determined and categorised according to the performance of the cabin crew at the exit [158]. The number of exits which comprise each of the Exit Delay Time settings is shown in Table 8.

From the collection of 22 video recordings of 90-second certification trials available to FSEG, no evacuation involving unassertive cabin crew positioned at exits of Type-C dimensions have been witnessed. This category is therefore empty (see Table 8). Furthermore, there were insufficient evacuations through Type-I exits to support being split into ASSERTIVE, INBETWEEN and UNASSERTIVE tiers. Thus for this exit type, an assertiveness category has not been defined for the curve that has been formed representing exit delays across the spectrum of crew assertiveness (see Table 8).

In addition during the development of passenger Exit Hesitation Delay distributions it was decided that cabin crew did no exert a significant affect on the exit hestiations delays experienced by passengers at canted Type-A exits. Thus, a single category of passenger exit hesitation delays was extracted (see Table 8). Likewise, cabin crew do not generally assist passengers at Type-III exits due to the narrow width of Type-III through-seating exit passageway(s). Instead, they tend to stand in or near the aisle and usher passengers into the exit seating row(s). As such, categorisation of exit hesitation delays by cabin crew assertion was considered irrelevant for this type of exit and only a single passenger exit hesitation delay was developed (see Table 8).

Table 8: Data used in forming the generalised parameter settings

	Number of exits on which the generalised setting is based			
Exit Type	**Exit Ready Time parameter (exits)**	**Assertive Exit Delay Time parameter (exits)**	**In-between Exit Delay Time parameter (exits)**	**Unassertive Exit Delay Time parameter (exits)**
Type-A	38	20	12	3
Canted Type-A	7	7		
Type-C	8	5	2	No data (as in-between)
Type-I	4	3		
Type-III (passenger operated)	9	12		
Type-III (crew operated)	1	12		

Another key parameter in airEXODUS is the Exit Ready Time. This attribute represents the time required by a crewmember or passenger to render the exit escape system ready for use. This attribute represents a slightly different series of events depending upon the specific procedures of a particular exit type.

For the Type-A exit escape systems the Exit Ready Time attribute represents the time for the cabin crew member to react to the call to evacuate, get out of their seat, move to the exit, contact the exit, open the exit and fully deploy the exit slide.

The Exit Ready Time parameter for canted Type-A, Type-B, Type-C and Type-I exits all represent a similar series of events. However, the Exit Ready Time parameter for the Type-III over wing exits represents a slightly different chain of events. It represents the time required for a passenger/crew member to react to the call to evacuate, get out of their seat, move to the exit, contact the exit, open the exit and dispose of the hatch.

3.10 Repeat simulations

airEXODUS is stochastic in nature. This means that every time a simulation is repeated a slightly different evacuation time will result, as the individual passengers are unlikely to exactly repeat their actions. In addition, as the passenger Exit Delay Time is randomly attributed according to the specified distribution, passengers will not necessarily incur the same Exit Delay Time on exiting the aircraft in subsequent simulations. For this reason, it is necessary to repeat a simulation numerous times in order to generate a distribution of results.

3.11 Validation history

Of all the aviation evacuation models, EXODUS appears to have the most extensive published verification history that incorporates all four validation components. Quantitative verification has been achieved using the results of 2 experiments (2-EX) [45], one blind wide-bodied analysis [45]. All of these validation tests have shown the model to correlate well with reality.

3.12 Relevant airEXODUS Parameters

Several airEXODUS parameters will be frequently referred to when describing the results of the model. These are; Personal Elapsed Time (PET), Total Evacuation Time (TET), Cumulative Wait Time (CWT), Distance, Response Time, Exit Ready Time, OPS, Flowrates and the Off-Time (see [36-38,40-52] for details).

The TET is a measure of the evacuation time for the aircraft. It is measured from the start of the evacuation to when the last passenger exits the aircraft. A single TET is determined for each evacuation simulation. Perhaps of more interest to an individual passenger is the PET. It is measured from the start of the evacuation to when the passenger has exited the aircraft. A PET is determined for each passenger in the evacuation simulation. The Response Time is the time a passenger takes to respond to the call to evacuate, release their seat restraint and stand. The Response Time is an attribute assigned to each passenger as part of the scenario definition.

The CWT measures the total amount of time a passenger has spent in congestion. This is measured after the passenger has completed their Response Time to when the passenger has exited the aircraft. This can include time spent in the seat row attempting to get into the aisle, time spent stationary in the aisle and time spent queuing at the exit. A CWT is determined for each passenger in the evacuation simulation.

The Exit Ready Time is the time required for the exit to be opened and made ready for use. The Exit Ready Time is an attribute assigned to each exit as part of the scenario definition. In these scenarios, the Exit Ready Time is set to 10.7 seconds so as to remove the Exit Ready Time variable. This time has been derived from the analysis of certification data (see Section 3.9).

The Off-Time is the time required for the passenger to reach the ground once they have mounted the slide. Like the passenger Exit Delay Time, this is derived from certification data. However, in this thesis off-times are always taken as zero. If on-ground times are desired, a suitable slide time can be added to the TET.

The Flow Rate parameter calculates the number of passengers that would evacuate within one minute of flow (see Equation (11)). The total number of passengers that have evacuated (PAX) is divided by the total flow time (TFT) for each exit (*i*). This yields the average number of passengers that evacuate for each second of the total flow time. This is multiplied by sixty to convert the measure to passengers/minute.

$$\textit{Flow rate (passengers/minute)} = \frac{PAX_i}{TFT_i}\ 60 \qquad (11)$$

TFT_i= Total Flow Time for exit i

PAX_i = Number of passengers that evacuated via exit i

The flow rate calculation reflects an average flow rate calculated from the total flow time of the exit. It does not provide information regarding the quality of the flow during specific periods, but merely forms an average for the total period of flow. Thus two very different patterns of flow could yield the same flow rate. It is therefore important to consider the pattern of flow in conjunction with the flow rate calculation.

In aircraft which have more than one exit available for evacuation, the total evacuation time will typically be reduced if the flow through each exit terminates at the same time. In optimal evacuation situations exit flows will be completed at approximately the same time. Sub-optimal cases occur when one or more exits exhaust their supply of paxs before the remaining exits.

As a measure of optimal performance FSEG have developed a statistic known as the OPS or Optimal Performance Statistic. The OPS measure has been described in detail in previous papers [37]. The OPS can be calculated for each evacuation, providing a measure of the degree of performance. The OPS is defined as follows,

$$OPS = \frac{\sum_{i=1}^{n} TET - EET_i}{(n-1) * TET} \qquad 12$$

n = number of exits used in the evacuation,

$\boldsymbol{EET_n}$ = Exit Evacuation Time (time last pax out) of Exit ***n*** (seconds),

TET = Total Evacuation Time (seconds) i.e. max[***EET***].

While it is unlikely that an aircraft will achieve an OPS = 0, near optimal performance will be marked by very low values of OPS. Selecting an acceptable value for OPS is somewhat arbitrary. For the purposes of this report we will consider OPS values of 0.1 or less as being optimal.

It is informative to plot the total evacuation time for an evacuation trial (or evacuation simulation) against the OPS, producing a plot similar to Figure 20.

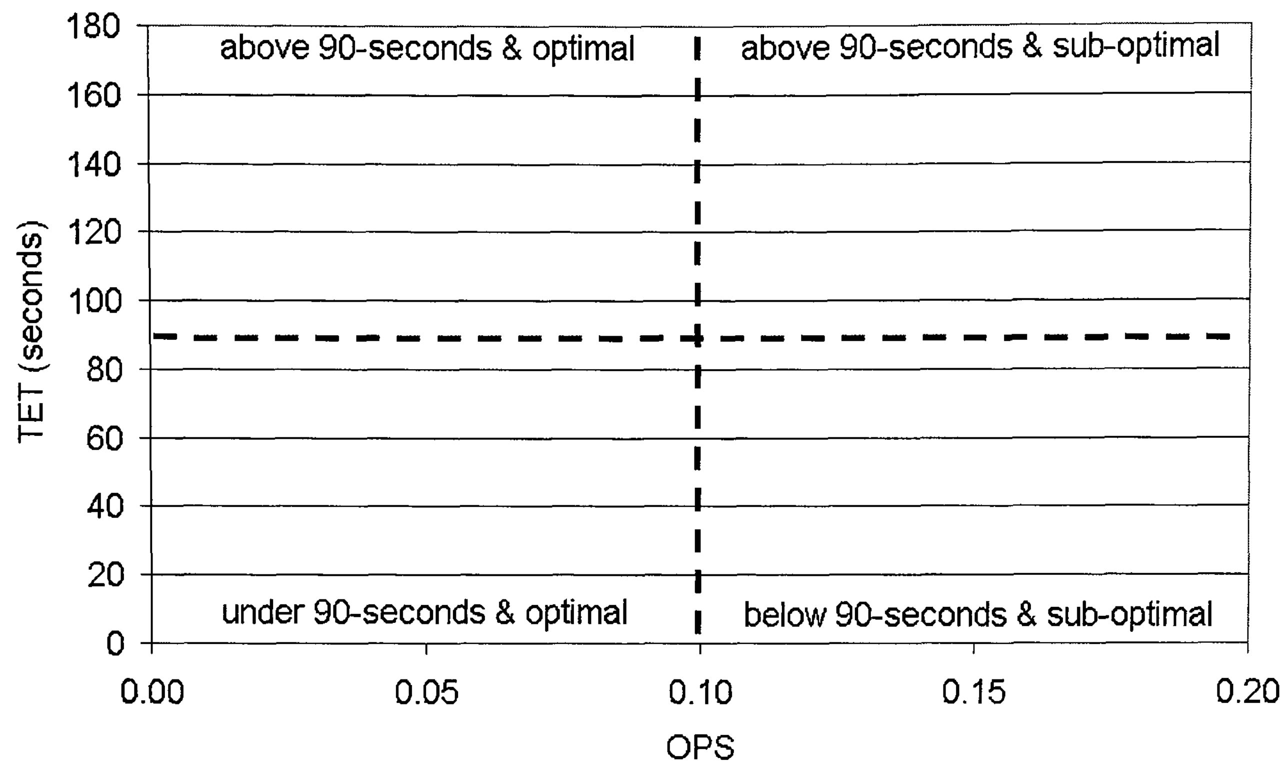


Figure 20: The four quadrants of evacuation time and performance level

The graph can be segmented into four quadrants linking the efficiency with which the aircraft evacuation was accomplished with the time required for the evacuation. These quadrants represent:

Quadrant 1, Bottom left:	Optimal evacuation with TET below 90 seconds
Quadrant 2, Top left:	Optimal evacuation with TET above 90 seconds
Quadrant 3, Bottom right:	Sub-optimal evacuation with TET below 90 seconds
Quadrant 4, Top right:	Sub-optimal evacuation with TET above 90 seconds

Depending on where the data point falls, various conclusions can be drawn concerning the performance of the aircraft. If the evacuation is repeated many times a scatter plot can be created. Whilst it is interesting to note where the bulk of the evacuations are positioned it is also useful to note the location of outliers.

An aircraft that repeatedly produces data points that are *optimal* and *above 90-seconds* (Quadrant 2) suggests that even when an evacuation is performed in an optimal manner the aircraft cannot achieve a TET of less than 90-seconds. In such aircraft, the evacuation procedures appear to be working as the passengers are well distributed between exits, yet the evacuation time is excessive. This would suggest that there is a fundamental design problem with the configuration of the aircraft.

At the opposite end of the spectrum are aircraft that produce evacuation times that are *sub-optimal* yet the TET is *below 90-seconds* (Quadrant 4). These aircraft are capable of generating acceptable evacuation times even when the evacuation is sub-optimal. Aircraft with the majority of evacuations within this quadrant demonstrate the desirable quality of being robust, as they are able to pass the 90-second criteria even when the evacuation efficiency is relatively low. This is a desirable property as it suggests that even when things go wrong with the crew procedures, it may still be possible to produce fast evacuation times. Furthermore, aircraft displaying this property are capable of producing improved evacuation times through procedural improvements such as the introduction of better passenger management procedures or better trained crew or configurationally through the introduction of an improved passenger distribution within the cabin.

An aircraft that generates evacuation times that are *sub-optimal* and *above 90-seconds* (Quadrant 3), while failing the 90-second criteria may still have the potential to improve its performance without requiring a major change to the configuration of the cabin. This suggests that the introduction of improved procedures or better trained crew may result in a reduction in evacuation times. However, this also suggests that the aircraft evacuation time is susceptible to suboptimal crew performance. If the crew perform in a suboptimal manner the evacuation time may become excessive. It should be noted that it is not recommended that complex and elaborate crew procedures be introduced simply to pass the 90 second criteria. It is also essential that the crew procedures are viable under actual emergency situations possibly involving fire.

Evacuation times that fall within the Quadrant 1 are both *optimal* and have TETs *under 90-seconds.* These aircraft have performed well and represent a good balance between procedures and configuration. It is unlikely that better times can be achieved for aircraft in this quadrant through procedural improvements. Evacuations within this quadrant are to be expected from a well orchestrated evacuation of a relatively good design.

3.13 Discussion of the current deficiencies of airEXODUS and their relation to the field of evacuation modelling

This section describes the key deficiencies of the airEXODUS evacuation model in the context of aircraft evacuation modelling technologies. In doing so it is possible to establish key areas that are in need of development in order to advance the field of evacuation modelling.

The first key criticism of airEXODUS when used for certification applications is the relatively small quantity and piece meal approach that has been taken to its validation thus far. Indeed the lack of systematic validation is not unique to airEXODUS but applies to the entire field of aircraft evacuation model. In order for evacuation modelling to be considered as a viable tool for the certification and design of aircraft it is critical that this area is addressed and that a more rigorous and systematic approach to validation is adopted.

The second criticism is its limited capabilities when simulating cabin crew behaviour. Whilst airEXODUS can currently model an deterministic imposed crew performance, it cannot predict the impact of crew procedures or provide insight into any proposed design. In real accidents and 90-second certification trials crew redirect/bypass passengers to/from exits within the cabin, as they react to the developing evacuation scenario. Whilst some basic explicit crew simulation is provided, such as opening/closing exits etc, this very important procedure is absent from the model.

In the context of the field of evacuation modelling technology in general, it is true that AIREVAC and GPSS had a rudimentary system of cabin crew redirection. However, these were based on simply counting the number of users for each exit and did not take into account the numerous likely factors that influence crew cabin management procedures. Indeed this was recognised by a report by the Office of Technical Assessment for the US congress in 1993 [1], which highlighted the inability of mathematical evacuation assessment models to simulate operator procedures. Thus, this failing must, again, be considered as a failing in the field of aircraft evacuation modelling.

The final criticism of airEXODUS V3.0 is that the basis for human behaviour is relatively simplistic. Within airEXODUS V3.0 passengers have no knowledge of the exits that they are going to use and merely know the next best node to occupy. In essence this dictates that passengers plan their route on a step by step basis essentially looking at their feet as they walk. In addition passengers do not have a mechanism for making decisions based on information obtained from the environment through their senses. This can lead to passengers blindly walking towards congested areas when alternative paths may exist. Likewise, the effects of smoke are limited.

As discussed in the previous chapter some other evacuation models have rudimentary decision based movement models for passenger route choice and exit selection. However, they are all very simplistic and none contain a satisfactory set of influences on passenger behaviour. Ideally, any decision making model should be empirically based and consider the multitude of possible influences such as: the flow pattern within the aircraft cabin and the density of passengers within the cabin, the environmental effects within the cabin (i.e. smoke, etc), the visibility afforded to each person within the cabin, and the effects of cabin crew on their decision making processes. The lack of a sufficiently detailed decision making model should, again, be considered a failing of the field of aircraft evacuation modelling technology.

3.14 Concluding remarks

This section has provided a detailed overview of the mechanics of the airEXODUS evacuation model and its current capabilities and when taken with Chapter 2 provides an answer to the question *"Are there currently evacuation models appropriate for certification and accident applications. If so what are they, what are they lacking?"*

This chapter has highlighted three main shortcomings of V3.0 of the airEXODUS model, they are,

1. the limited quantity of validation,
2. the limited ability of the model to represent crew procedures in both 90-second certification trials and real emergency evacuations,
3. the rudimentary/unadaptive and in some cases lack of models of human behaviour in real emergency scenarios.

The three issues that were highlighted should be considered as failings in the field of aircraft evacuation modelling in general and block the progression of this technology in becoming viable tools for the certification and design of passenger aircraft. As such each of these issues will be tackled in turn in the remainder of this thesis and in doing so evacuation modelling technology advanced.

4 An assessment of the capabilities of airEXODUS V3.0 to simulate 90-second certification trials

4.1 Introduction

This chapter poses and to some degree answers the *question "Can the results of a model be trusted, verified and interpreted?"* In this context, this chapter examines the capabilities of the airEXODUS to simulate the current aircraft evacuation performance benchmark – the 90-seconds certification trial. This involves subjecting the model to a battery of qualitative and quantitative tests. In order for the user to have confidence in the results produced by the evacuation model, it is crucial that they are comprehensively evaluated and as much as possible shown to be accurate. This section undertakes such an assessment.

In the validation study undertaken in this chapter, the 90-second certification trials of four previously certified wide-bodied and two previously certified narrow-bodied aircraft will be simulated. This evaluation will assess the performance of the model in two ways. Firstly, its underlying accuracy at reproducing the results of 90-second certification trails is assessed. This can be achieved via using the data from the actual trails to specify model parameters a technique that is explained in more detail later. Using this technique the fundamental accuracy of the model can be gauged using the 'best' information that is available. Following from this, the capability of airEXODUS when used to predict the results of 90-second certification trials is evaluated. When used to predict the results of a 90-second certification trial the model is configured with 'generalised data' (in essence 'average data') based on performance levels measured from many aircraft evacuations. This approach will allow an assessment of the accuracy of the model when used to predict future 90-second certification trials.

Using these techniques the most comprehensive set of aircraft evacuation model validation is performed to date. In doing so, arguments as to the fundamental validity of the 90-second certification trial methodology as a means of ranking aircraft evacuation performance are raised.

4.2 The certification trial cases

This section details the certification trial cases that will be utilised in the validation analysis presented in this report.

4.2.1 The limitations of 90-Second Certification trial data for the validation of evacuation models

Before continuing it is important to appreciate the limitations of data derived from certification trials when used to validate aircraft evacuation models. This section provides a brief discussion of the use of certification trial data for validating aircraft evacuation models. More general information concerning the validation of aircraft evacuation models can be found in the work of Galea [41] and has already been discussed (see Section 2.3.2).

It is important to appreciate that a single certification trial result for a particular aircraft should not be taken or assumed to represent the mean TET for the trial, as the single data point could lie anywhere on a frequency distribution of likely results (see Figure 21). In the same way, a single airEXODUS simulation generates only a single TET data point. However, unlike certification trials, it is possible to run airEXODUS many times to generate a distribution of TETs that reflects the variation within the experimental scenario. Thus, airEXODUS is typically used to generate a TET distribution. It is from the airEXODUS generated TET distribution that a mean TET can be derived.

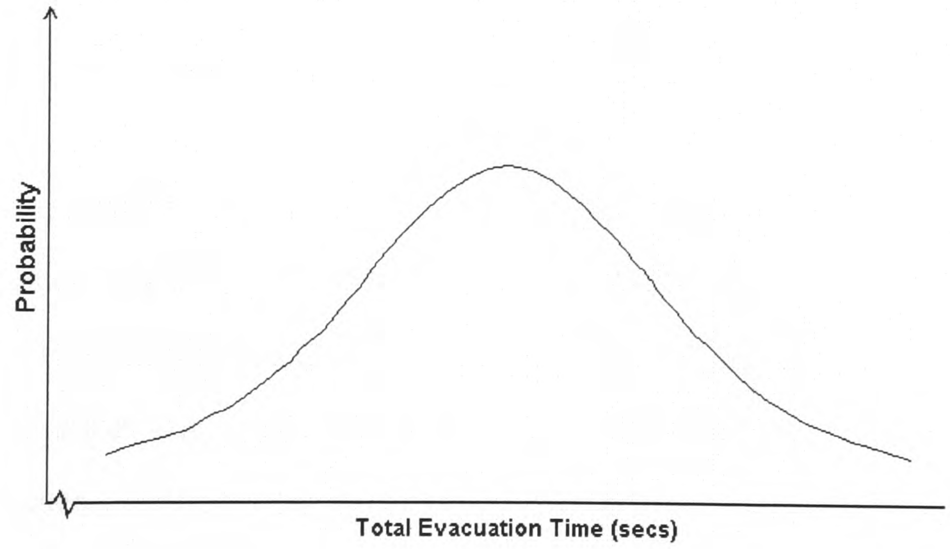


Figure 21: Hypothetical Distribution of the Probability of Specific Total Evacuation Times

Difficulties arise when comparing a mean TET generated by airEXODUS with a single data point from a single 90-second certification trial. When comparing model predictions with the trial result, a positive agreement would be achieved if the actual certification trial result falls within the predicted distribution. It is difficult to make a more definitive statement concerning the actual trial result and the model predictions. A more demanding comparison between model predictions and experimental results can be made by comparing the predicted time out for each passenger with that derived from the certification trial. In this case, the trial results are compared with the window of predicted results generated by taking the maximum and minimum time out for each passenger throughout the entire range of repeat simulations.

4.2.2 Selection criteria

In order to undertake a detailed evacuation analysis requires a significant amount of effort. It was therefore not practical to attempt to perform validation analysis on all the certification trials available (22 in total). It was therefore necessary to select appropriate cases for analysis. Primary selection was dictated by the provision of a detailed aircraft cabin layout description in the certification trial documentation. Having established that a suitable diagram existed and that a model could therefore be defined, additional filtering criteria were applied to the certification trials.

It would advantageous to indicate whether airEXODUS can predict the potentially small differences that may arise between derivative aircraft belonging to a single aircraft family. Thus, derivative aircraft were favoured by the author – both narrow- and wide-bodied aircraft. In addition, it was desirable to select aircraft that had a variety of exit types.

In order for the results of airEXODUS to be comparable to the results of a certification trial the OPS values for both should be similar. Optimality, as measured by the OPS parameter - i.e. OPS values less than 0.1 - is a good baseline to adopt as it indicates that the aircraft evacuation was well executed. An OPS score was calculated for each of the candidate cases. Where the optimality was above the critical value of 0.1, the certification trial case was rejected. Problems may arise when cases are selected with an OPS = 0.1. These are border line cases that may display considerable sub-optimality in some areas.

Those certification trial cases that were considered optimal - i.e. OPS < 0.1 - were then examined for ***significant cabin crew intervention*** such as directed bypass or passenger initiated redirection. Cabin crew directed bypass is defined as a procedure in which a cabin crewmember redirects passengers past an exit in the cabin section to another exit in the cabin section. This is employed to more evenly balance the number of passengers to the exits given their evacuation capabilities. Passenger initiated redirection is where passengers redirect from their initial exit choice to an alternative exit. Both of the above could lead to significant periods of exit non-flow or single lane flow. Furthermore as mentioned in the previous chapter airEXODUS does not currently have an adequate representation of cabin crew procedures. Thus, where cabin crew directed bypass and/or passenger initiated redirection had a ***major affect*** on the evacuation the cases were discounted.

A final check for serious abnormalities - such as passengers refusing to evacuate - were then undertaken. Where found these cases were also rejected on the grounds that they would be difficult to model and even more difficult to predict. The selection process resulted in a total of six certification trials. Four aircraft were wide bodied and two were narrow bodied. Of the four wide-bodied aircraft three were derivatives of the same series. Both of the narrow-bodied aircraft were derivatives of the same series. Finding suitable narrow-body cases for examination was difficult either because the certification video footage was quite old and difficult to study in detail, or the cases failed or nearly failed the selection criteria. As a result, the two narrow-body cases finally selected are less than ideal but are the best of the cases available.

4.2.3 Descriptions of cases

4.2.3.1 Certification Case 1 (255 passengers)

This certification trial was the first in a series of derivative wide-bodied aircraft that were studied. The aircraft seated 255 passengers and was configured with three pairs of exits. Type-A exits were positioned at either end of the passenger cabin sections. These exits were labelled R1 and R3. A pair of Type-III over wing exits accessible over seating was located at approximately the centre of the cabin section, approximately in line with the wing. This exit was designated L2. Seat rows were in a

2-3-2 configuration with each seat row separated by an aisle. The cabin section was div le in the centre of the cabin.

The last passenger evacuated the cabin section via the R1 exit after **83.7** seconds. Calculating an OPS score (see Equation 2) for trial case 1 reveals that this aircraft meets the OPS criterion (OPS $\leq$ 0.1) scoring a value of **0.1**. The majority of the passengers evacuated via the forward and aft Type-A exits. The type-III overwing exit generated much lower flowrates than the forward and aft Type-A exits. Manufacturer procedures for this aircraft indicated to the crew that only a small number of passengers should use the over wing exits as their flow rates were likely to be low. Some cabin crew directed passenger bypass occurred during this certification trial. In the certification trial approximately **6%** of those passengers that evacuated via the R1 exit were bypassed from the Type-III over wing exit. This resulted in a **3** second period of passenger 'no-flow' at the R1 exit towards the end of the evacuation. No bypass to other exits was observed.

4.2.3.2 Certification Case 2 (285 passengers)

This aircraft seated 285 passengers and was configured with four pairs of exits. Type-A exits were located at both the forward and aft end of the cabin section and are labelled R1 and R4. Two Type-III over wing exits were positioned in the centre of the cabin section and are labelled R2 and R3. The two Type-III exits were positioned adjacent to each other. These Type-III exits were accessed via a small clear space vestibule common to both Type-III exits. Seat rows were in the 2-3-2 configuration with an aisle separating each seat block. The total passenger seating was divided into two sections by a cross aisle in the centre of the cabin section adjacent to the two Type-III exits. The last passenger evacuated the cabin at **72.6** seconds via the R3 Type-III over wing exit. This trail generated an OPS score of **0.06,** thereby satisfying our certification criterion (OPS $\leq$ 0.1). The Type-A exits evacuated the majority of the passengers which conformed to the manufacturer's procedures for this aircraft, which indicated to cabin crew that these exits would achieve higher flow rates than the Type-III exits and should therefore receive more passengers. During the certification trial the R1 and R4 exits generated much higher flow rates than the mid-section Type-III exits. The cabin crew at the Type-III exit bypassed some passengers. The bypass resulted in passengers switching from one Type-III exit to another. The alternative Type-III exit was positioned immediately adjacent (within 0.5 metres). Any resulting delay to passengers' evacuation is considered minimal.

4.2.3.3 Certification Case 3 (351 passengers)

This aircraft is the most recent in the series of derivative wide-bodied aircraft that is examined as part of this study. This aircraft seats 351 passengers. The aircraft contains four pairs of exits. Type-A exits were positioned in the forward and aft sections and are labelled R1 and L4. A canted Type-A exit was positioned just before the leading edge of the wing and was labelled R2. A Type-I exit was positioned just after the trailing edge of the wing and was labelled L3. The cabin section was divided into three seating sections by a cross aisle and clear space vestibule area. In each seating section the seat rows were generally in the 2-4-2 configuration with each seat block separated by an aisle.

The last passenger evacuated the cabin section after **71.7** seconds via the R1 exit. Calculating an OPS score for this case yields a value of **0.05** and therefore meets our optimality criterion (OPS $\leq$ 0.1). The three Type-A exits generated higher flow rates than the mid-section Type-I exit. Some cabin crew directed bypass occurred during this certification trial. Ten percent of those passengers that evacuated via the R1 exit were bypassed from the mid-section. Of the passengers that evacuated via the aft exit (L4), eight percent were bypassed from the mid section. None of these bypass operations resulted in periods of exit 'non-flow'.

4.2.3.4 Certification Case 4 (440 passengers)

This aircraft is from a different family of wide-bodied aircraft to the previous derivative aircraft series. The aircraft seated 440 passenger and was configured with four Type-A exits. The two mid-section exits were canted. From forward to aft the exits were labelled L1-L4. Seat rows were generally in the 3-4-3 configuration with each seat block separated by an aisle. The fuselage tapered at the forward and aft positions, thus the number of seats abreast was reduced in these areas. The cabin section was broken into three sections by cross aisles and clear space vestibule areas adjacent to the mid-section exits.

The last passenger evacuated the cabin section via the L1 exit after **74.4** seconds. An OPS score of **0.05** was generated by this certification trial and the evacuation is therefore classed as optimal (OPS $\leq$ 0.1). The majority of passengers evacuated via the mid-section exits. The bias towards more passengers evacuating via the mid-section exits, resulted from the mid-section exit's comparatively high flow rates coupled with a low OPS value for the aircraft as whole. Some cabin crew directed bypass occurred during this certification trial. This resulted in approximately a third of the passengers that evacuated via the R1 exit and **13%** of passengers that evacuated via R4 exit being bypassed from the mid-section.

4.2.3.5 Certification Case 5 (149 passengers)

This certification trial is the first in a series of derivative narrow-bodied aircraft that was examined. The aircraft seated 149 passengers and had three pairs of exits in total. Type-C exits were positioned at either end of the passenger cabin sections. These exits have been labelled R1 and R3. A further pair of Type-III over wing exits accessible over seating was located at approximately the centre of the cabin section, approximately in line with the wing. This exit was designated as R2. Seat rows were in a 3-3 configuration with a central separating aisle.

The last passenger evacuated the cabin section through the R2 exit after **64.1** seconds. This aircraft meets the optimality criterion (OPS ≤ 0.1) scoring a value of **0.02**. The majority of passengers evacuated via the forward and aft exits (R1 and R3). These exits generated the highest flow rates. A small number of passengers evacuated through the centrally located over wing exit (R2). This exit generated the lowest flow rate. Some cabin crew directed passenger bypass occurred during this certification trial. Flight and cabin crew had taken up positions in an aisle seat two/three rows forward and aft of the Type-III exit performed some passenger redirection. In the certification trial approximately **5%** of those passengers that evacuated via the R1 exit were bypassed from the Type-III over wing exit. The bypass did not result in any major periods of exit inactivity, i.e. non-flow. Bypass was not observed to other exits.

4.2.3.6 Certification Case 6 (188 passengers)

This certification trial was the second in the series of derivative narrow-bodied aircraft examined in this report. This aircraft seated 188 passengers and was configured with four pairs of exits in total. Type-C exits were positioned at either end of the passenger cabin. These exits have been labelled R1 and R4. Two pairs of Type-III over wing exits accessible over seating were located at approximately the centre of the cabin section, roughly in line with the wing. These exits were designated as R2 and R3. The two Type-III exits were positioned in adjacent seat rows. Seat rows were in a 3-3 configuration with a central separating aisle.

The last passenger evacuated the cabin section at **78.5** seconds through R2. An OPS score of **0.1** was calculated from the exit finishing times and just meets our optimality criterion (OPS $\leq$ 0.1). The two Type-C exits generated relatively high flow rates compared with the two Type-III exits. The cabin crew created a split in the cabin section such that the majority of passengers evacuated via the Type-C exit positioned at the forward and aft of the aircraft. Examination of video footage of this certification trial revealed that the only bypass that occurred was locally between the adjacent R2 and R3 exits. The forward exit (R1) finished evacuating passengers before the other exits. This is reflected in the OPS score of **0.1** generated by the certification trial. This indicates that some passengers at the R2 and R3 exits could have been bypassed towards the R1 exit. Should this have occurred, it is likely that both the evacuation time and optimality score of this certification trial would be reduced.

4.3 Model configuration

4.3.1 Definition of parameters used within airEXODUS

As mentioned previously two settings for the passenger Exit Delay Time and Exit Ready Time parameters will be used for each certification trial case that will be considered in this study.

The first setting is referred to as the 'Actual data'. The Actual data settings represent the actual passenger exit delay and exit ready times extracted from video evidence of each exit on each aircraft. This parameter represents the actual timings exhibited during the certification trials. Using the 'Actual data' setting should enable airEXODUS to model the Exit Delay Times and Exit Ready Times achieved on the day as accurately as possible. This will demonstrate the ability of airEXODUS to reproduce the results of a certification trial when given the actual data from the certification trial.

The second setting is referred to as the 'Generalised data'. The Generalised data represents an average setting that has been derived from multiple certification trials. Use of the generalised passenger exit delay time data enables airEXODUS to make predictions of the evacuation performance of new configurations, based upon the average performance derived from the analysis of many previous certification trials. Generalised settings have been determined for each of the five exit types.

4.3.2 Passenger Behaviour

While airEXODUS has the ability to represent "extreme" passenger behaviour of the type reported in actual aviation accidents [90,6], such as seat jumping, this type of behaviour is not included in this assessment as they are not considered features of the 90-second certification scenario. All the cases considered here are run under certification evacuation conditions involving:

- Half the total number of aircraft exits,
- Assertive cabin crew located at each Type-A exit,
- Orderly passenger behaviour of the type found in certification evacuations,
- Each exit being made ready in a representative time derived from past relevant certification tests.

An optimal distribution of passengers to each exit was determined for all of the aircraft considered in this study. In this way the model was configured so that it was likely that an optimal evacuation would be achieved. As the model was set up to produce optimal results, adaptive procedures such as cabin crew initiated bypass or passenger initiated redirection were not explicitly modelled.

4.3.3 Population Specification

Passengers defined in airEXODUS are created using the 90-second Population function available in the software. This function generates the required numbers of passengers according to the specified mix (in terms of age and gender) as set out in FAR 25.803 [12]. In addition, the Patience attribute was set at a very large value for all the simulations in order to model a compliant (non-competitive) population. Passengers when attributed with infinite patience will always wait patiently in queues whilst moving towards their nearest exit. Listed in Table 9 are the range of core attributes generated for the passenger populations.

Table 9: Core passenger attribute ranges used in the airEXODUS simulations

Attribute	Min	Max	Mean
Drive	1.19	14.99	9.82
Walk (m/s)	0.26	0.60	0.49
Fast Walk (m/s)	0.52	1.20	0.99
Response Time (s)	0.02	8.00	3.93

4.3.4 Constructing airEXODUS geometries

A schematic of the interior cabin arrangement of each aircraft was provided with each of the certification trial reports. From these diagrams, the aircraft geometries were constructed within the model using techniques that have been described in previous work [37,38,44-47,41] and this thesis (see Chapter 3).

4.3.5 Defining the scenarios

Once the aircraft geometries were defined within airEXODUS and populated with representative passengers two different sets of scenarios were defined. To ensure that the base models for each of the scenarios were identical in every respect the aircraft models were cloned.

To define the two scenarios the first clone was assigned passenger exit delay times and exit ready times in accordance with the actual data (see Section 4.2). The passenger exit delay times and exit ready times of the second clone were then set in accordance with the generalised settings (see Section 4.2). This procedure yielded two slightly different scenarios for each aircraft (see Table 10). The first scenario made use of the actual data from the certification trial whereas the second scenario made use of generalised data.

Table 10: Scenario description for each of the validation cases

Aircraft	Scenario 1 (Data utilised in copy 1)	Scenario 2 (Data utilised in copy 2)
Case 1	Actual data	Generalised data
Case 2	Actual data	Generalised data
Case 3	Actual data	Generalised data
Case 4	Actual data	Generalised data
Case 5	Actual data	Generalised data
Case 6	Actual data	Generalised data

4.4 Results and discussion of the wide-bodied validation scenarios

4.4.1 Reconstructing the results of wide-bodied certification trials using the actual exit hesitation time data

This section evaluates the ability of airEXODUS to reproduce the results of the certification trials using the actual passenger exit delay times and exit ready times. This series of validation cases will give an indication of how close airEXODUS can get to the results of the actual certification trial.

As the certification trial is a benchmark it provides us with a way of ranking aircraft evacuation performance. For the computer model to be considered representative of, or equivalent to the certification trial, the ranking of aircraft by the model should be broadly equivalent to that generated by the trial. In this section the ability of airEXODUS to rank aircraft will be examined.

A summary of the trial results and the model predictions can be found in Table 11 and Figure 22. For the family of derivative aircraft, the rank ordering of the certification trial results places Case 3 with the quickest evacuation time, followed by Case 2 and lastly case 1. Examination of the data in Table 11 demonstrates that airEXODUS reproduces the same rank ordering when the mean time from the airEXODUS distribution is used to rank the aircraft.

Table 11: Trial and airEXODUS results for certification trial cases 1-4 using the actual data

Case / Aircraft	Trial Result (secs)	airEXODUS mean (secs)	Standard deviation	# standard deviations trial from airEXODUS mean	Trial rank	airEXODUS rank
Case 1	83.7	86.6	2.2	1.32	4	4
Case 2	72.6	70.4	2.6	0.85	2	2
Case 3	71.7	68.2	2.3	1.52	1	1
Case 4	74.4	76.9	1.8	1.39	3	3

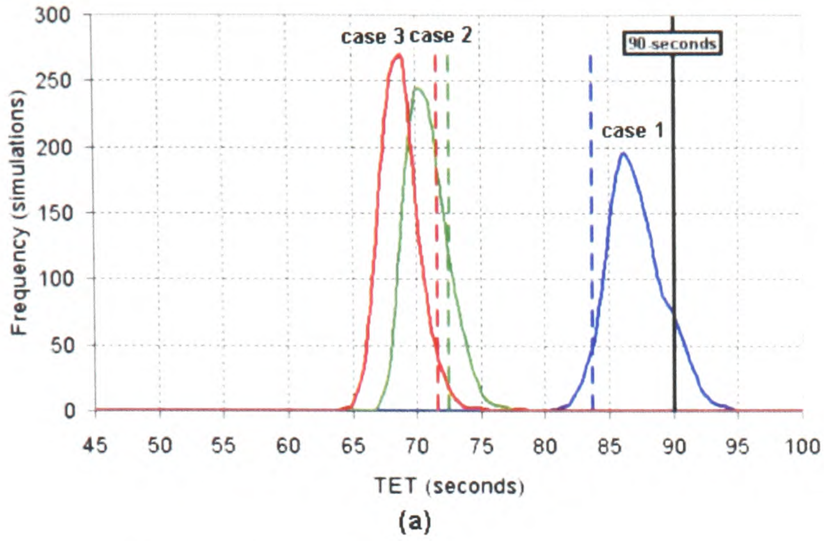
Furthermore, the relative differences between the various aircraft performances generated by airEXODUS match those observed in the actual certification trials. Closer examination of Figure 22(a) reveals that the difference between the certification trials (Dashed lines in Figure 22) of Case 2 and Case 3 were only small, i.e. the dashed lines are close together, whereas the difference between certification trials of Case 2 and Case 1 was large. It can be seen in Figure 22(a) that airEXODUS broadly reproduces these features. The airEXODUS generated TET frequency distributions of Case 2 and Case 3 are relatively close together, whereas the airEXODUS generated TET frequency distributions of Case 2 and Case 1 are reasonably far apart.

At this point it is important to raise a note of caution in the above analysis concerning the rank ordering of the aircraft. As the actual performance (and model simulated performance) of an aircraft is defined by a probability distribution, it is possible for the rank ordering of the aircraft - as gauged by a single data point - might change with repeated trials. Thus the rank ordering achieved by the certification trials single data point is not truly indicative of the rank ordering of the performance capabilities of the aircraft. This will be the case if the probability distributions for any two aircraft overlap.

To demonstrate this let us assume that the model generated probability distributions for each aircraft accurately represents the actual frequency distribution. We see from Figure 22b that these frequency distributions all overlap to a certain extent. Thus if we were to select one time at random from each distribution to represent that actual time achieved in the certification trial we would obtain a particular rank order. If we were to select a second point at random from each distribution it is possible that we would obtain a completely different rank ordering – due to the overlap. Thus the rank ordering achieved in the certification trials cannot be taken as a definitive measure of the relative ranking and hence relative performance of the aircraft. Thus, it may in fact be fortuitous that the rank ordering achieved by airEXODUS and the certification trials agree. This issue is further discussed in Section 4.7.

To summarise, airEXODUS has demonstrated that it is able to reproduce the rank order of each of the derivative aircraft. Furthermore airEXODUS is capable of capturing the relative differences in the performances of each of the derivative aircraft. However, the rank ordering produced by the certification trials is subject to variation due to the probabilistic nature of the trials.

The frequency distribution of TETs for Case 4 – which is not part of the family of aircraft examined in Cases 1-3 – is presented along with the results for the first three cases in Figure 22(b). Looking first at the times generated by the certification trials, it can be seen that the evacuation time measured in the certification trial of case 4 is positioned between the times measured for case 2 and case 1. It can be seen that the frequency distributions that were generated by airEXODUS demonstrate exactly the same ordering. In addition, the TET frequency distribution for Case 4 has been correctly placed in between the TET frequency distribution of Case 1 and Case 2. In other words, airEXODUS is able to correctly rank order all of the wide-bodied cases considered and in doing so capture the major quantitative differences between each of the cases.



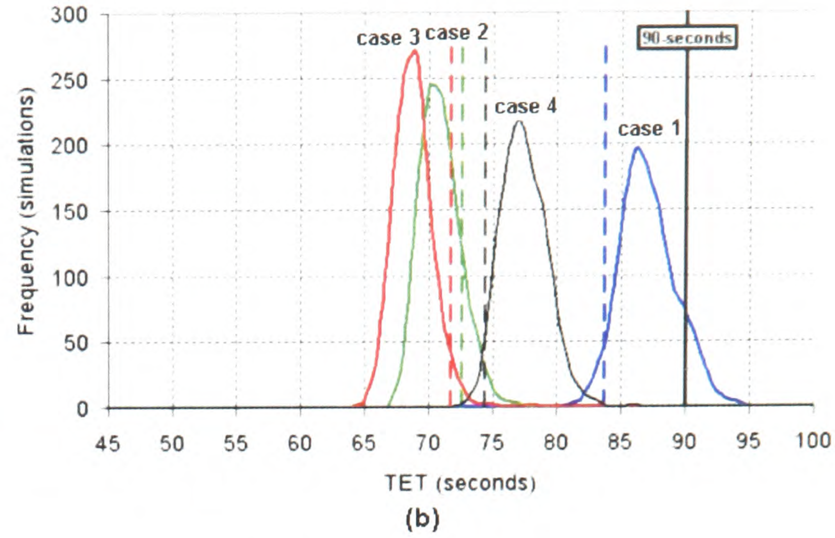


Figure 22: Combination of frequency distributions generated by airEXODUS using the actual data (a) the derivative cases 1- 3 and (b) all cases 1-4

Having established that airEXODUS can reproduce the general trends of the certification trials we now examine the differences between airEXODUS predictions and the evacuation times of the certification trials.

Table 12: Summary of the comparisons between the results of the certification trial cases and the airEXODUS results when using the actual data from the certification trials

	Case 1	Case 2	Case 3	Case 4	Mean of absolute difference
Difference between airEXODUS mean TET and trial TET (%)	3.5%	3%	4.9%	3.4%	3.7%
Difference between airEXODUS mean TET and trial TET (secs)	2.9	2.2	3.5	2.5	2.8
Standard deviation					
trial TET within bounds of airEXODUS TETs	YES	YES	YES	YES	N/A
Probability that the aircraft will fail (number of simulations)	76	0	0	0	N/A
Probability that the aircraft will fail (%)	7.6%	0	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	1.6	0	0	0	N/A

Firstly, we note that in each case the evacuation time of the actual certification trial was within the range of values predicted by airEXODUS. In other words, airEXODUS is generating results that include the result of the certification trial. Table 12 also reveals that the magnitude of the difference (in seconds) between the mean TET generated by airEXODUS and the evacuation time achieved in the certification trials. As shown, the differences range from 2.2 to 3.5 seconds with a mean absolute difference of 2.8 seconds. These results suggest that when using the actual data from the certification trial airEXODUS can produce a mean TET that is within 3.0% to 4.9% of the result of the actual certification trial (or 3.7% on average).

In two cases the airEXODUS mean was higher than the result of the certification trial and in two cases the airEXODUS mean was lower thus, airEXODUS is not consistently over or under predicting the certification results. Furthermore, the degree of over- or under-prediction is small, with an average absolute mean difference of 3.7% (2.8 seconds).

As mentioned previously, the evacuation time generated in each of the certification trials represents only one data point from a hypothetical distribution of data points. It could be that a certification trial that generated an evacuation time that was higher than the airEXODUS mean performed worse than the average certification trial of the aircraft. Conversely a certification trial that generated an evacuation time that was lower than the airEXODUS mean could have performed better than the average certification trial of particular aircraft. The differences between the mean TETs of airEXODUS and the evacuation time of the certification trials could originate from A) error in airEXODUS at simulating the events and/or B) the intrinsic unreliability associated with performing a single certification trial.

In conclusion, given the lack of multiple data points for each certification trial it is difficult to make definitive statements concerning how accurate airEXODUS reproduces the certification trials. However, we can improve our level of confidence through the number of certification trials with which airEXODUS is compared. airEXODUS has consistently shown that it is capable of producing a range of TETs that both include the evacuation time generated in the certification trial and produce a mean that is reasonably close to the evacuation time of the certification trial. More confidence can be derived from the fact that airEXODUS is reproducing the comparative trends, i.e. the correct rank order of the aircraft.

4.4.2 Predicting the results of wide-bodied certification trials using the generalised data

The previous section demonstrated that airEXODUS could reproduce the results of certification trials with reasonable accuracy when supplied with the actual data from the certification trial. In the absence of data from the actual certification trial, airEXODUS makes use of generalised data appropriate to the exit type. This generalised data is based upon numerous previous evacuation certification trials. If demonstrated as feasible, this approach allows a *prediction* based on a appropriate generalised data for the aircraft. In this section we re-evaluate the certification trials using the generalised data within airEXODUS.

Generalised data will be applied to both passenger exit delays and to the time required to ready an exit for use. In these cases cabin crew performance is uniformly fixed as assertive. The time required to ready an exit for use will be set to an average value that was derived from the analysis of certification trials (see Section 4.2.3). Apart from the aforementioned variables all of the parameters will remain identical to the previous section. This will enable a direct comparison with the results using the actual data.

A summary of the trial results and the model predictions can be found in Table 13 and Figure 23. Examination of the data in Table 13 demonstrates that, when using the generalised data, airEXODUS is still capable of reproducing the same rank ordering of aircraft performance as is achieved in the actual certification trials.

Table 13: Trial and airEXODUS results and rank order for certification trial cases 1-4 using the generalised data

Case / Aircraft	Trial Result (secs)	airEXODUS mean (secs)	Standard deviation	# standard deviations trial from airEXODUS mean	Trial rank	airEXODUS rank
Case 1	83.7	82.7	5.1	0.20	4	4
Case 2	72.6	73.1	2.2	0.23	2	2
Case 3	71.7	68.3	2.4	1.42	1	1
Case 4	74.4	77.9	2.7	1.30	3	3

Once again, it is important to note that the rank ordering produced by the certification trials should not be taken to indicate a definitive rank ordering due to the probabilistic nature of evacuation performance.

Having established that airEXODUS can predict the general trends, i.e. rank ordering, of the certification trials, we can now examine how the means of the TETs generated by airEXODUS compare with the measured evacuation time of the certification trials. Similarly to the reconstruction cases of the previous sections, confidence in the predictive ability of the model using generalised data can be derived from the fact that in every case the evacuation time of the certification trial was within the range of values predicted by airEXODUS. When using the generalised data airEXODUS predicts TETs that include the evacuation time of the certification trial.

The differences between the airEXODUS mean TET and the evacuation time of the certification trials is shown in Table 14. It can be seen that the difference between the airEXODUS mean TETs and the evacuation time measured in the actual certification trials range from 0.5 to 3.5 seconds (0.8% to 4.7%). Two of the cases generated mean TETs that were very close to the TET of the certification trial, i.e. 1.2% (1.0 seconds) and 0.8% (0.5 seconds). The remaining two cases were within 4.7% of the measured result.

The mean absolute difference across all cases was 2.8% (2.1 seconds). Returning to the results from the certification reproduction cases (i.e. using the actual data), we note from Table 12 that the maximum difference between the airEXODUS mean and the actual evacuation time achieved in the certification trials was 4.9% (3.5 seconds) with an average variation between all of the actual cases of 3.7% (2.8 seconds). Contrasting the results of the actual and generalised cases reveals that the results have not greatly altered.

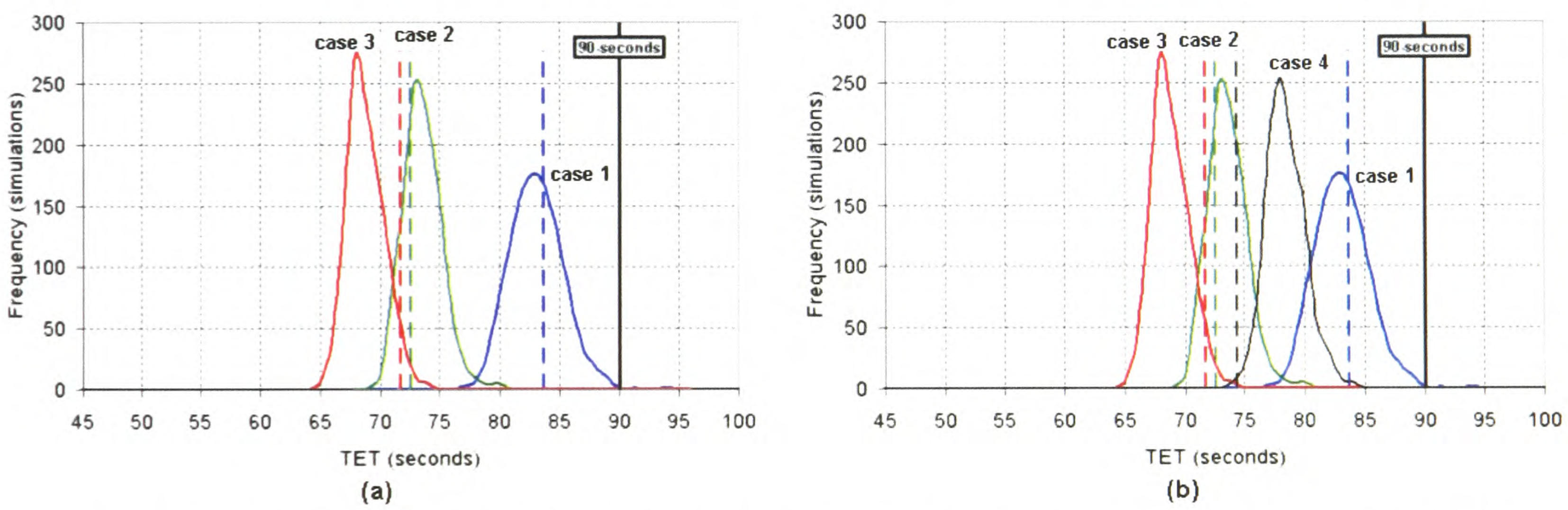


Figure 23: Combination of frequency distributions generated by airEXODUS using the generalised data for (a) the derivative cases 1- 3 and (b) all cases 1-4

Table 14: Summary of the comparisons between the results of the certification trial cases and the airEXODUS results when using the generalised data

	Case 1	Case 2	Case 3	Case 4	Mean of absolute difference
Difference between airEXODUS mean and trial TET (%)	1.2%	0.8%	4.7%	4.7%	2.8%
Difference between airEXODUS mean and trial TET (secs)	1.0	0.5	3.4	3.5	2.1
trial TET within bounds of airEXODUS TETs	YES	YES	YES	YES	N/A
Number of simulations in excess of 90 seconds (simulations)	3	Nil	Nil	Nil	N/A
Number of simulations in excess of 90 seconds (%)	0.3%	Nil	Nil	Nil	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	3.3	Nil	Nil	Nil	N/A

However, as is to be expected when using generalised data, there are some differences between the predicted and measured trends. For example, a feature of the certification trials was that the difference between the evacuation time of Case 3 and Case 2 was small (see the dashed lines on Figure 23(a)) while using the generalised data we predict a larger difference. The actual difference between the performance of these two aircraft was 0.9 seconds or 1.3%. Using the actual data, this difference was 2.2 seconds or 3.2% while using the generalised data the difference was 4.8 seconds or 7.0%. Thus, while the rank ordering of the two aircraft is correctly predicted using the model, when the generalised data is used we have a greater relative difference between the performance of these two aircraft.

This can again be seen by comparing the relative performance achieved in Case 3 and Case 1. The actual difference between the performance of these two aircraft was 12 seconds or 16.7%. Using the actual data, this difference was 18.4 seconds or 27.0% while using the generalised data the difference was 14.4 seconds or 21.1%. Once again, while the rank ordering of the two aircraft is correctly predicted using the model, when the generalised data is used we have a lower relative difference between the performance of these two aircraft.

Thus, while using the generalised data, the model has not been able to correctly predict the magnitude of the differences between the cases, the model has correctly predicted the trends in the differences, namely that the difference between Cases 3 and 2 will be relatively 'small' while the difference between Cases 3 and 1 will be relatively 'large'. Finally, it is worth recalling here that the trial results are only the result of a single experimental trial. Had more trial results been generated, the relative difference between the trial means could be very different.

To summarise, airEXODUS appears to be able to predict the results of the certification trial using the generalised data with at least as much accuracy as in the previous cases. In all of the wide-bodied cases the measured evacuation time of the certification trial is within the bounds of airEXODUS predictions. Additionally the difference between the airEXODUS generated means and the measured evacuation time of the certification trial is not significantly altered when using the generalised data compared with the actual data. While general trends in the results such as the rank ordering have been maintained, there are some differences in the nature of the frequency distributions produced by the generalised and actual data.

4.4.3 Examining the predicted and measured evacuation evolution of the wide-bodied certification trials

The ability of airEXODUS to generate TETs that are reasonably close to the evacuation time of the certification trial is of major importance. However, simply predicting the total evacuation time is insufficient as this is simply a measure of the degree to which the model fits only a single measured quantity (i.e. the TET). It is possible to arrive at a good estimate of the end point for all the wrong reasons, thereby providing a misleading representation of the aircraft performance. It is therefore also essential that the model correctly predicts the evolution of the evacuation.

One measure of the manner that the evacuation evolves is provided by cumulative exit performance. This is a measure of the total number of passengers to exit the aircraft in each second of the evacuation. The cumulative number of passengers who have exited the aircraft at every second during the certification trial can be compared against the results generated by airEXODUS. In this way the airEXODUS predictions can be compared against the performance of the certification trial throughout the evacuation.

In airEXODUS the personal evacuation time (PET) of each passenger is recorded. From this the cumulative number of passengers who have exited the aircraft in each second of the evacuation can be determined. This process can be repeated for each of the repeat simulations. For the series of simulations presented previously a simulation envelope can be defined by taking the minimum and maximum number of passengers who have exited the aircraft in each second. For the simulations considered here, each case was repeated 1000 times. The simulation envelope for each scenario represents the minimum and maximum from 1000 simulations. Thus, each of the 1000 repeat simulations will produce a curve that falls within the envelope. In addition, the median of the 1000 airEXODUS simulations can be determined.

This predicted window of cumulative exit timings can be compared with the actual results derived from each certification trial. In order to construct the cumulative exit curve for the certification trial it is necessary to study the video recording of the actual certification trial. Video recordings of each certification trial were inspected and the time that each passenger exited the aircraft was noted. Using this data, the cumulative number of passengers who have exited can be determined at every second of the actual evacuation. These results were then plotted as a function of time and compared with the model generated curves.

4.4.3.1 Validating the airEXODUS prediction for the evolution of wide-bodied certification trials using the actual data

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the four aircraft is shown in Figure 24. As can be seen from the curves, initially there is a period during which no passengers evacuate whilst the doors are readied for use. This is typically followed by a short period during which the passenger flow is established. This is marked by the rapid initial increase in gradient at around 10 seconds. Very quickly the exits are at near maximum flow capacity, indicated in Figure 24 by a near constant positive gradient. This state persists for the majority of the evacuation. Near the end of the evacuation, when the supply of passengers to exits begins to diminish the gradient also begins to diminish. The flow terminates when there are no more passengers to evacuate.

It can be seen that airEXODUS predictions produce similar structure to the certification trial. This indicates that airEXODUS is predicting a similar chain of events to that which occurred during the certification trial.

Furthermore, it can be seen that the results from the certification trials, denoted by the black lines in Figure 24, are totally within the airEXODUS simulation envelopes for Case 1, Case 2 and Case 3. This suggests that at each second of the evacuation airEXODUS is producing a similar number of evacuees to that which occurred in the certification trial.

However, for Case 4 (B777-200) we note that between 35 and 60 seconds the certification trial curve crosses outside of the airEXODUS simulation envelope, but is within a +/-5% error band drawn around the minimum and maximum times. This minor departure from the simulation envelope indicates that the certification trial performed marginally better than airEXODUS during this period. This may result from an abnormally high exit flow rate during this period. Further examination reveals that it is a minor excursion from the airEXODUS envelope and that the results of the certification trial quickly return within the simulation envelope. In general it is apparent that at every second of the evacuation airEXODUS is generating similar results to the certification trials.

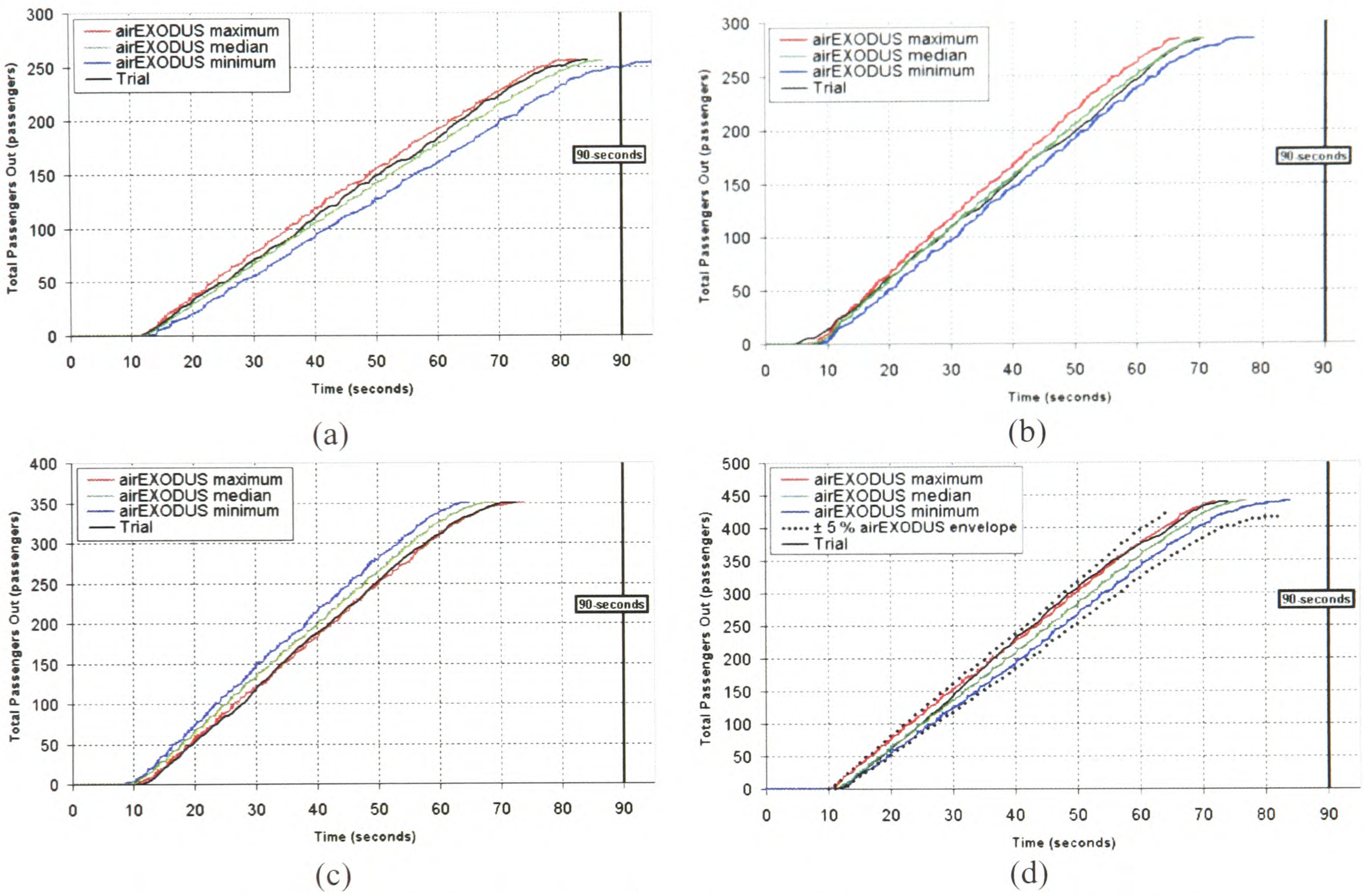


Figure 24: airEXODUS simulation envelope generated using the actual data and actual trial results for (a) Case 1, (b) Case 2, (c) Case 3 and (d) Case 4

4.4.3.2 Validating the airEXODUS prediction for the evolution for wide-bodied certification trials using the generalised data

The airEXODUS simulation envelope generated using the generalised data can be seen in Figure 25. As described in the previous section, the curves generated by the generalised data follow the general trends observed in the trials. The envelopes are similar in shape to those generated using the actual data (see Figure 25). Furthermore, for each of the wide-bodied cases examined, for the vast majority of the evacuations, the certification trial curve falls within the simulation envelope generated by airEXODUS.

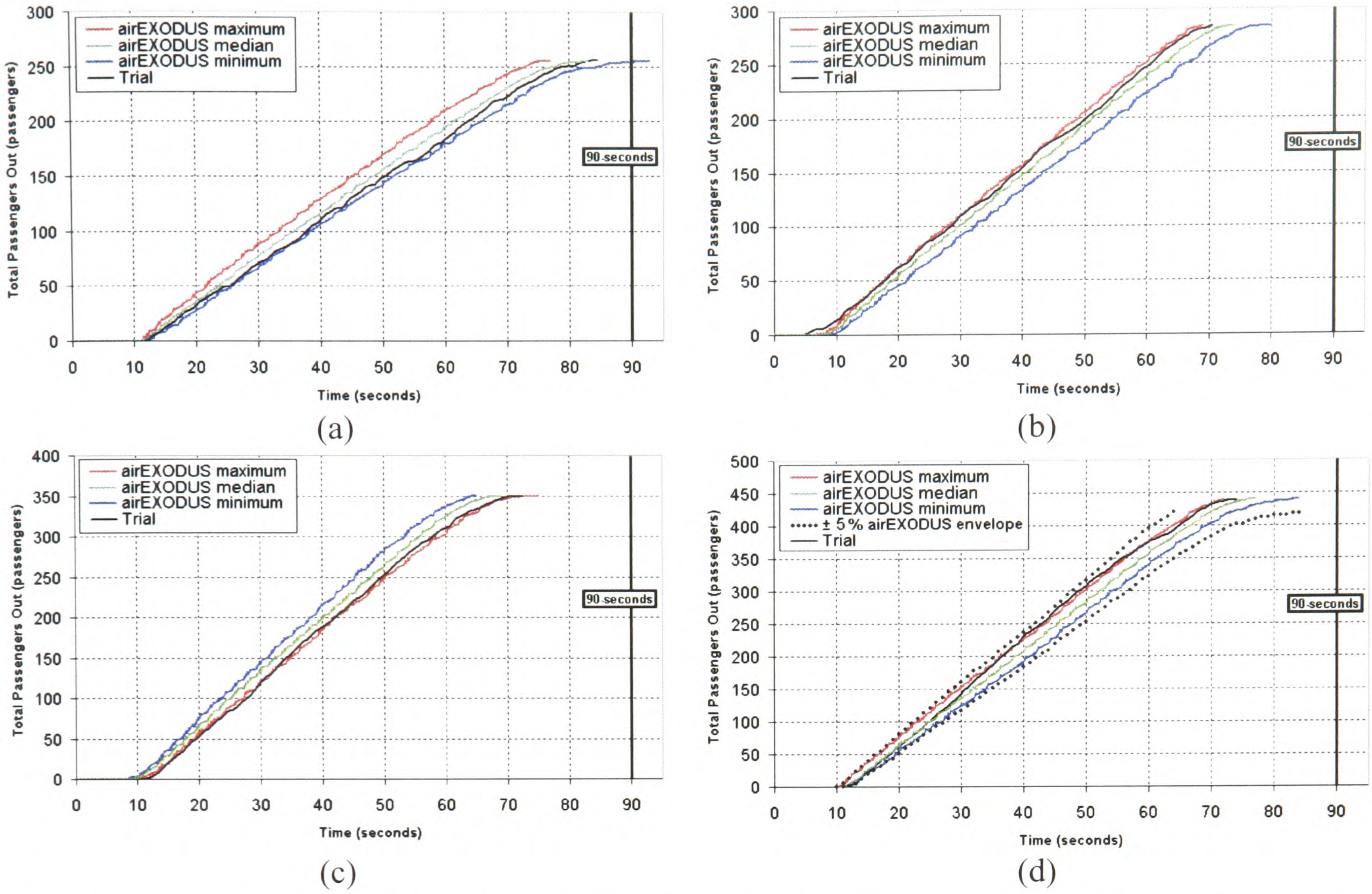


Figure 25: airEXODUS simulation envelope generated using the generalised data for (a) Case 1, (b) Case 2, (c) Case 3 and (d) Case 4

As with the case for the actual data, we find that for Case 4 we note that between 40 and 55 seconds the certification trial curve crosses outside of the airEXODUS simulation envelope, but is again within a +/-5% error band drawn around the minimum and maximum times. This minor departure from the simulation envelope indicates that the certification trial performed marginally better than airEXODUS during this period. In general it is apparent that at every second of the evacuation airEXODUS is generating similar results to the certification trials.

4.4.4 Summarising the outcome of the airEXODUS reconstructions and predictions for wide-bodied certification trials

Several key points can be made from the analysis of the wide-bodied results:

1a) Using the actual data from specific certification trails, airEXODUS is able to produce distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

1b) Using the generalised certification trial data, airEXODUS is able to predict distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

2a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank three derivative aircraft in the identical order that was achieved in the certification trials. However, it should be noted that a ranking based on a single certification trial result for each aircraft may not be indicative of the actual ranking of the aircraft.

2b) Using the generalised certification data, airEXODUS was able to successfully rank three derivative aircraft in the identical order that was achieved in the certification trials.

3a) Using the actual data from the specific certification trials, airEXODUS was able to closely predict the relative and absolute differences between the rank ordering.

3b) Using the generalised certification data, airEXODUS was able to closely predict the relative differences between the rank ordering, while the absolute differences could not be predicted with a high degree of certainty due to the natural differences that occur in specific certification trials.

4a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank the performance of an additional aircraft not related to the original three derivative aircraft.

4b) Using the generalised certification data, airEXODUS was able to successfully rank the performance of an additional aircraft not related to the original three derivative aircraft.

5a) Using the actual data from specific certification trials, airEXODUS predicted that one of the four aircraft (one of the aircraft in the three aircraft derivative family), while having a strong possibility of passing the certification trial, has a small probability that it could fail the certification criterion.

5b) Using the generalised certification data, airEXODUS predicted that the same aircraft had a small probability of failing the certification criterion. However, the probability of failure was smaller using the generalised data.

6) The cumulative exit curves for each of the four aircraft examined fall within the numerical envelope predicted using airEXODUS and the generalised certification data. This suggests that airEXODUS is capable of predicting the time evolution of the evacuation using the generalised data.

Thus, whether the model makes use of the generalised or actual trial data, an engineer using the model would come to the same conclusions regarding the TET of the aircraft and the evolution of the aircraft evacuation. Of more importance however, the mean TET predicted using the generalised data is a good indicator of the likely performance of the aircraft in the actual certification trial. In addition to predicting the mean TET and the evacuation evolution, the model can also estimate the likelihood of failure and identify potential problem areas with the cabin layout. This is an important conclusion as it suggests that airEXODUS has the capability of predicting the likely distribution of Total Evacuation Times under optimal certification conditions.

4.5 Results and discussion of the narrow-bodied validation scenarios

In this section we continue the validation of airEXODUS using data from narrow body aircraft trials.

4.5.1 Reconstructing the results of narrow-bodied certification trials using the actual exit hesitation time data

As in the wide-bodied aircraft analysis, the **actual** data will be utilised to establish how accurately airEXODUS can match the results of the actual certification trial. The actual distribution of passenger exit delay times experienced at each exit were extracted from the video record for each of the exits used on each aircraft and used in the simulations. Similarly the actual time required to ready each exit for use was measured and assigned to each of the exits within airEXODUS.

It can be seen that the rank ordering of the derivative narrow-bodied aircraft during their respective certification trials shows that Case 5 was the fastest and that Case 6 was the slowest (see Table 15). The mean TETs and rank ordering generated by airEXODUS can be seen in Table 15. It is apparent that when using the actual data airEXODUS ranks the aircraft in the same order as the certification trial.

Once again, it is important to note that the rank ordering produced by the certification trials should not be taken to indicate a definitive rank ordering due to the probabilistic nature of evacuation performance. This issue is further discussed in section 4.7.

The airEXODUS generated frequency distribution for these aircraft can be seen in Figure 26. From the TET frequency distribution it is apparent that the relative differences between the two derivative narrow-bodied aircraft was greater in the certification trials (indicated by dashed lines) than predicted by airEXODUS.

Table 15: Trial and airEXODUS results and rank order for certification trial cases 5 and 6 using the actual data

Case / Aircraft	Trial Result (secs)	airEXODUS prediction (secs)	Standard deviation	# standard deviations trial from airEXODUS mean	Trial rank	airEXODUS rank
Case 5	64.1	70.5+	2.7	2.37	1	1+
Case 6	78.5	73.0	1.7	3.24	2	2

+ More than 25% of these airEXODUS results were sub-optimal

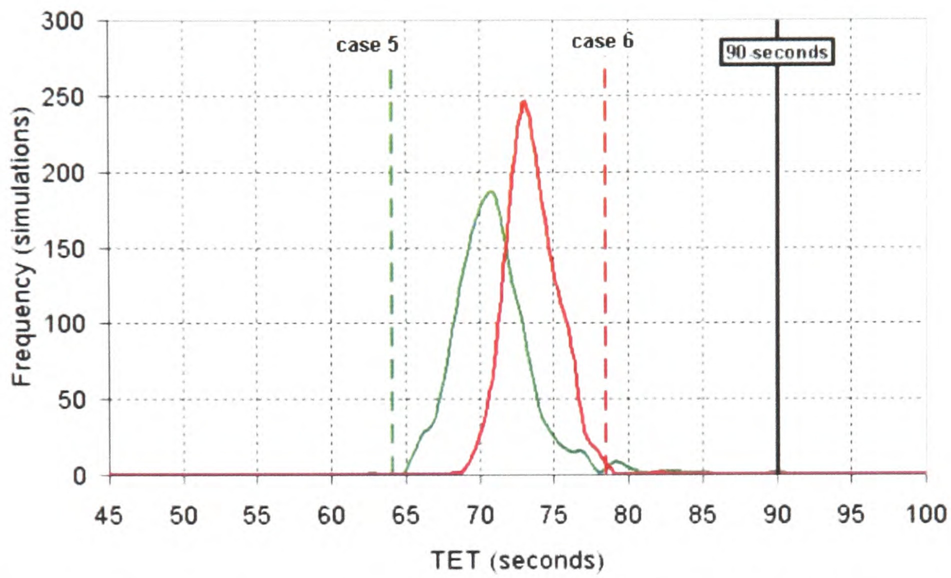


Figure 26: Combination of frequency distributions generated by airEXODUS using the actual data for the narrow-bodied derivative cases 5 and 6

The relative difference between the certification trial results for these two aircraft is **14.4** seconds (see Table 15). However, the difference between the airEXODUS generated means for these two cases was only **2.5** seconds. Thus, while the airEXODUS simulations have correctly predicted the performance rank ordering of these two aircraft, the relative difference between the two aircraft has not been correctly predicted. airEXODUS predicts that the differences between the two aircraft are small while the trial results suggest that there is a more significant difference.

Table 16: Summary of comparison between the results of the certification trial cases and the airEXODUS predictions when using the actual data

	Case 5	Case 6	Mean of absolute difference
Difference between airEXODUS mean and trial TET (%)	10.0% (8.4%)+	7.0%	8.5% (7.7%)+
Difference between airEXODUS mean and trial TET (secs)	6.4 (5.4)+	5.5	5.9 (5.5)+
trial TET within bounds of airEXODUS TETs	YES	YES	N/A
Number of simulations in excess of 90 seconds (simulations)	0	0	N/A
Number of simulations in excess of 90 seconds (%)	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	N/A	N/A	N/A

+ airEXODUS results with an OPS > 0.1 are excluded

However, the discrepancies that were noted in each case act so as to compound the differences between the two aircraft. In Case 5 airEXODUS generated a significant number of sub-optimal cases (38.4% were sub-optimal) which effectively increased the mean TET for these predictions. This had the effect of moving the TET frequency distribution towards longer evacuation times. In a report submitted to the CAA [49], it was demonstrated that if the sub-optimal cases were removed from the analysis – thereby bringing the simulations into line with the observed trial - the mean TET would be reduced from 70.5 seconds to 69.5 seconds. A reason for the failure of the model to generate a result similar to the trial is that the model lacks the capability of simulating crew redirection procedures which were employed during the actual certification trial. This issue was highlighted as a potential deficiency of V3.0 of the software and will be developed in later chapters of this thesis.

In Case 6, effectively the opposite problem occurred. In this case, the trial achieved a relatively poor level of optimality, producing an OPS = 0.1, compared with a predicted mean OPS of 0.05. This had the effect of pushing the predicted TET frequency distribution towards shorter evacuation times. Had a more optimal distribution of passengers been achieved during the trial, it is possible that the measured TET would have been reduced, bringing it closer to the predicted mean TET. When airEXODUS is configured to provide a similar level of OPS to that achieved in the trial the predicted mean TET is increased from 73.0 seconds to 76.0 seconds.

Taking these two factors into account, the difference between the predicted TETs for the two cases increases to 6.5 seconds, which is more inline with the observed difference. These two factors in conjunction with the limitations of having only a single trial data point for each case explain the variation in the relative differences.

To summarise, when using the actual data airEXODUS is able to successfully rank both of the narrow-bodied derivative aircraft. The mean absolute difference between the certification trial results and the mean TET generated by airEXODUS was 8.5%. This relatively large difference results from disparities in the levels of optimality that could be achieved in the airEXODUS simulations and that achieved during the actual certification trials. Should optimality in all of the cases have been low then the mean absolute difference would have been reduced.

4.5.2 Predicting the results of narrow-bodied certification trials using the generalised data

The previous section demonstrated that airEXODUS could reproduce the results of certification trials with reasonable accuracy when supplied with the actual data from the certification trial. In the absence of data from the actual certification trial, airEXODUS makes use of generalised data appropriate to the exit type. This generalised data is based upon numerous previous evacuation certification trials. If demonstrated as feasible, this approach allows a *prediction* based on a generalised data for the aircraft. In this section we re-evaluate the certification trials using the generalised data within airEXODUS.

Similar to the analysis of the wide-bodied aircraft, the generalised data will be applied to both passenger exit delays and to the time required to ready an exit for use. In these cases cabin crew performance is uniformly fixed as assertive. The time required to ready an exit for use will be set to an average value that was derived from the analysis of certification trials (see Section 4.2.3). Apart from the aforementioned variables all of the parameters will remain identical to the previous section. This will enable a direct comparison with the results using the actual data later in this report.

Table 17 shows the results of the certification trial evacuations and the mean TETs generated by airEXODUS when using the generalised data. As can be seen, the airEXODUS predictions generated using the generalised data rank the aircraft in the same order as was achieved in the actual certification trials i.e. the evacuation performance of Case 5 is better than the evacuation performance of Case 6.

Examination of the TET frequency distribution generated by airEXODUS when using the generalised data is shown as Figure 27. It can be seen that the relative difference between the evacuation times of the certification trial (indicated by the dashed lines) is greater than the relative difference between the maximum frequencies of the airEXODUS curves.

The relative difference between the certification trial results for these two aircraft is **14.4** seconds (see Table 17). However, the difference between the airEXODUS generated means for these two cases is **4.4** seconds. Thus, while the airEXODUS simulations have correctly predicted the performance rank ordering of these two aircraft, the relative difference between the two aircraft has not been correctly predicted. airEXODUS predicts that the differences between the two aircraft are small while the trial results that there is a more significant difference.

Table 17: Trial, airEXODUS results and rank order for certification trial cases 5 and 6 using the generalised data

Case / Aircraft	Trial Result (secs)	airEXODUS prediction (secs)	Standard deviation	# standard deviations trial from airEXODUS mean	Trial rank	airEXODUS rank
Case 5	64.1	65	2.1	0.43	1	1
Case 6	78.5	69.4	1.7	5.35	2	2

Table 18: Summary of the comparisons between the results of the certification trial cases and the airEXODUS results when using the generalised data

	Case 5	Case 6	Mean of absolute difference
Difference between airEXODUS means and trial TET (%)	1.4	11.6	6.5
Difference between airEXODUS means and trial TET (secs)	0.9	9.1	5.0
trial TET within bounds of airEXODUS TETs	YES	NO	N/A
Number of simulations in excess of 90 seconds (simulations)	0	0	N/A
Number of simulations in excess of 90 seconds (%)	0	0	N/A
Distance between 90 second and airEXODUS mean (standard deviations)	N/A	N/A	N/A

The difference between the airEXODUS mean TET and the certification results in each case is shown in Table 18. It can be seen that the mean TET generated by airEXODUS is relatively close (within 1.4% or 0.9 seconds) to the time recorded during the certification trial evacuation of Case 5. However the mean TET generated by airEXODUS in Case 6 is 11.6% (9.6 seconds) from the time recorded during the certification trial evacuation. The mean absolute difference between the airEXODUS means and the results of the certification trial is 6.5% (5.0 seconds). Whilst in Case 5 the result of the certification trial falls within the range of TETs generated by airEXODUS, in Case 6 the result of the certification trial does not fall within the range of TETs generated by airEXODUS.

It is important to recall the disparity in the level of optimality achieved in airEXODUS and during the certification trial of Case 6. In addition to this, differences are expected to result when comparing an average performance of passengers and crew - the generalised data - against a single performance during a single evacuation.

This is to be expected, as has already been discussed, the certification performance of the Case 5 was more optimal than one would normally expect while the certification performance of the Case 6 was considerably worse than the model indicates could be achieved, thus compounding the measured difference between the two aircraft.

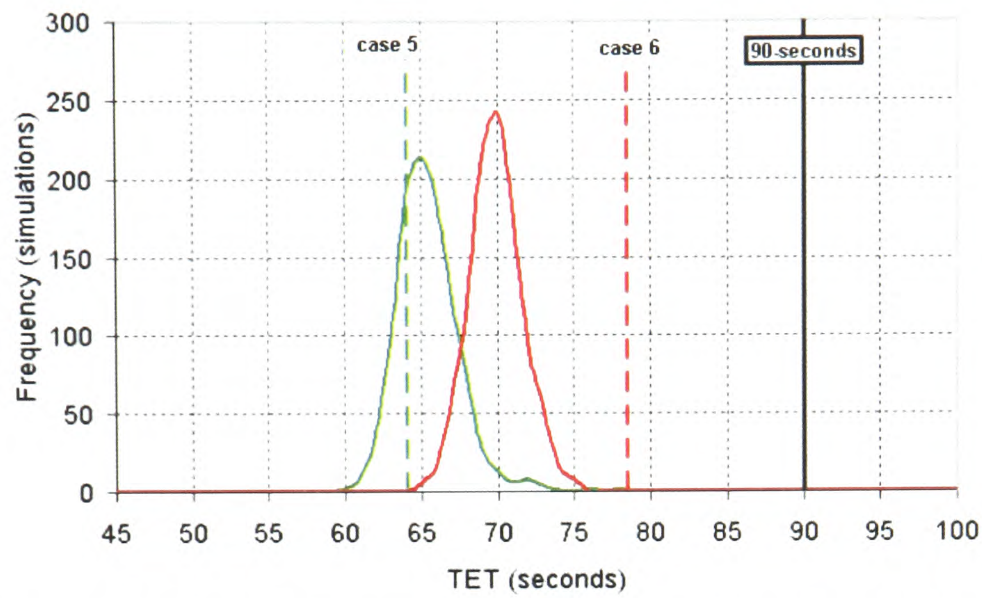


Figure 27: Combination of frequency distributions generated by airEXODUS using the generalised data for the narrow-bodied derivative cases 5 and 6

To summarise, when using the generalised data airEXODUS is able to rank the derivative narrow-bodied aircraft in the same order as the certification trials. The relative difference between the aircraft is not as pronounced as is suggested by the certification trial. This results in part from the relative sub-optimality of the certification trial evacuation for Case 6. The modelling results also suggest that both aircraft did not perform as would normally be expected, with the Case 5 performing better than expected and Case 6 performing considerably worse than expected. This highlights the difficulties in making comparisons based on only two data points from single evacuations.

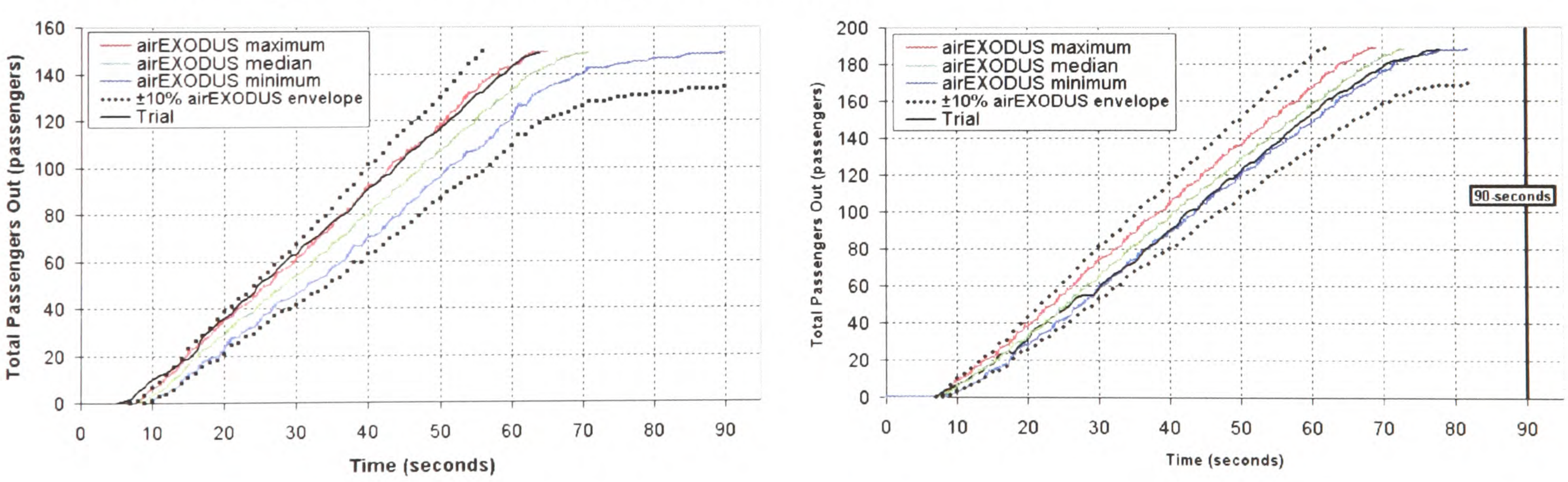
4.5.3 Examining the predicted and measured evacuation evolution of the narrow-bodied certification trials

In this section we examine the ability of airEXODUS to predict the evolution of the narrow-bodied aircraft evacuation. Recall from Section 4.4.3 that a simulation envelope can be determined from the results of airEXODUS. The results from the certification trial is then compared with the airEXODUS generated simulation envelope at every second of the evacuation.

4.5.3.1 Validating the airEXODUS prediction for the evolution of narrow-bodied certification trials using the actual data

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the two aircraft is shown in Figure 24. As can be seen from the curves, initially there is a period during which no passengers evacuate whilst the doors are readied for use. This is typically followed by a short period during which the passenger flow is established. This is marked by the rapid initial increase in gradient at around 10 seconds. Very quickly the exits are at near maximum flow capacity, indicated in Figure 24 by a near constant positive gradient. This state persists for the majority of the evacuation. Near the end of the evacuation, when the supply of passengers to exits begins to diminish the gradient also begins to diminish. The flow terminates when there are no more passengers to evacuate.

The airEXODUS cumulative exit envelope predicted using the actual data, together with the result of the certification trials for each of the narrow body aircraft is shown in Figure 28. In Case 6, it can be seen that the result of the certification trial is within the bounds of the simulation envelope. However, Case 5 falls outside the bounds of the envelope initially and remains marginally outside the envelope for the first 35 seconds. This suggests that in Case 5, the model was initially under-predicting the speed at which the passengers were exiting the aircraft.



(a) (b)

Figure 28: The airEXODUS simulation envelopes generated using the actual data for (a) Case 5 and (b) Case 6

This discrepancy is quite small and is within a +/-10% error bands defined around the model window. Recall that the absence of cabin crew redirection in the airEXODUS models was proposed as a possible reason for the differences between the TETs generated by airEXODUS and that achieved during the 90-second certification trial.

This explanation cannot explain the discrepancy shown in Figure 28 as cabin crew redirection procedures would not have an influence until near the end of the evacuation. A possible explanation of this discrepancy could be the nature of the population distribution generated by airEXODUS. For each of the 1000 repeat simulations each of the passengers had the same seating allocation. Thus if slow passengers were seated in crucial positions they would always be in those positions and thus could adversely affect the result of the simulation. After examining Case 5 it was found that this was indeed the situation. In this case, slow passengers with relatively long response times were situated in the front rows on the aisle seats. Thus they delayed the start up of the evacuation process and thus may have caused the initial discrepancy in the results. This is an important observation and has a bearing on the nature in which certification simulation cases should be run.

To investigate this possibility, simulations were repeated – with the same population as was used in Case 5 - but several different approaches were tried to randomise the population. In the first approach a single randomisation of the seating allocation was generated and the simulation repeated 1000 times. This generated a distribution with a mean TET of 68.8 seconds (see Table 19). This represents a reduction in TET of 1.7 seconds or 2.4%. The second approach consisted of three randomised seat allocations each run 333 times and the third case consisted of 10 randomised seat allocations each run 100 times. As can be seen from Table 19 and Figure 29, each of the different randomised selections produced similar results and all of them are different to the original single randomised selection.

Table 19: Results from an airEXODUS sensitivity analysis for Case 5 of passenger seat allocations using the actual data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Actual Data (Original) 61.6% OPS <0.1	**Min**	7.6	62.9	22.0	35.0	0.00
	Mean	**8.3**	**70.5**	**24.5**	**37.8**	**0.09**
	Max	9.9	89.8	27.5	40.9	0.28
	STD	0.4	2.7	0.8	0.9	0.04
Actual Data (single randomised seat allocation) 85.9% OPS <0.1	**Min**	6.9	62.6	21.7	34.9	0.00
	Mean	**7.1**	**68.8**	**23.9**	**37.1**	**0.06**
	Max	8.1	86.6	26.8	40.2	0.25
	STD	0.2	2.8	0.8	0.8	0.03
Actual Data (3 randomised seat allocations) 84.7% OPS <0.1	**Min**	6.9	62.6	21.3	34.5	0.00
	Mean	**7.1**	**68.9**	**23.7**	**37.0**	**0.06**
	Max	8.1	86.3	26.8	40.2	0.25
	STD	0.2	3.0	0.8	0.8	0.04
Actual Data (10 randomised seat allocations) 69.3% OPS <0.1	**Min**	6.9	62.8	21.1	34.4	0.00
	Mean	**7.1**	**69.3**	**23.6**	**36.8**	**0.08**
	Max	8.6	84.9	26.9	40.2	0.25
	STD	0.3	3.0	0.9	0.9	0.04

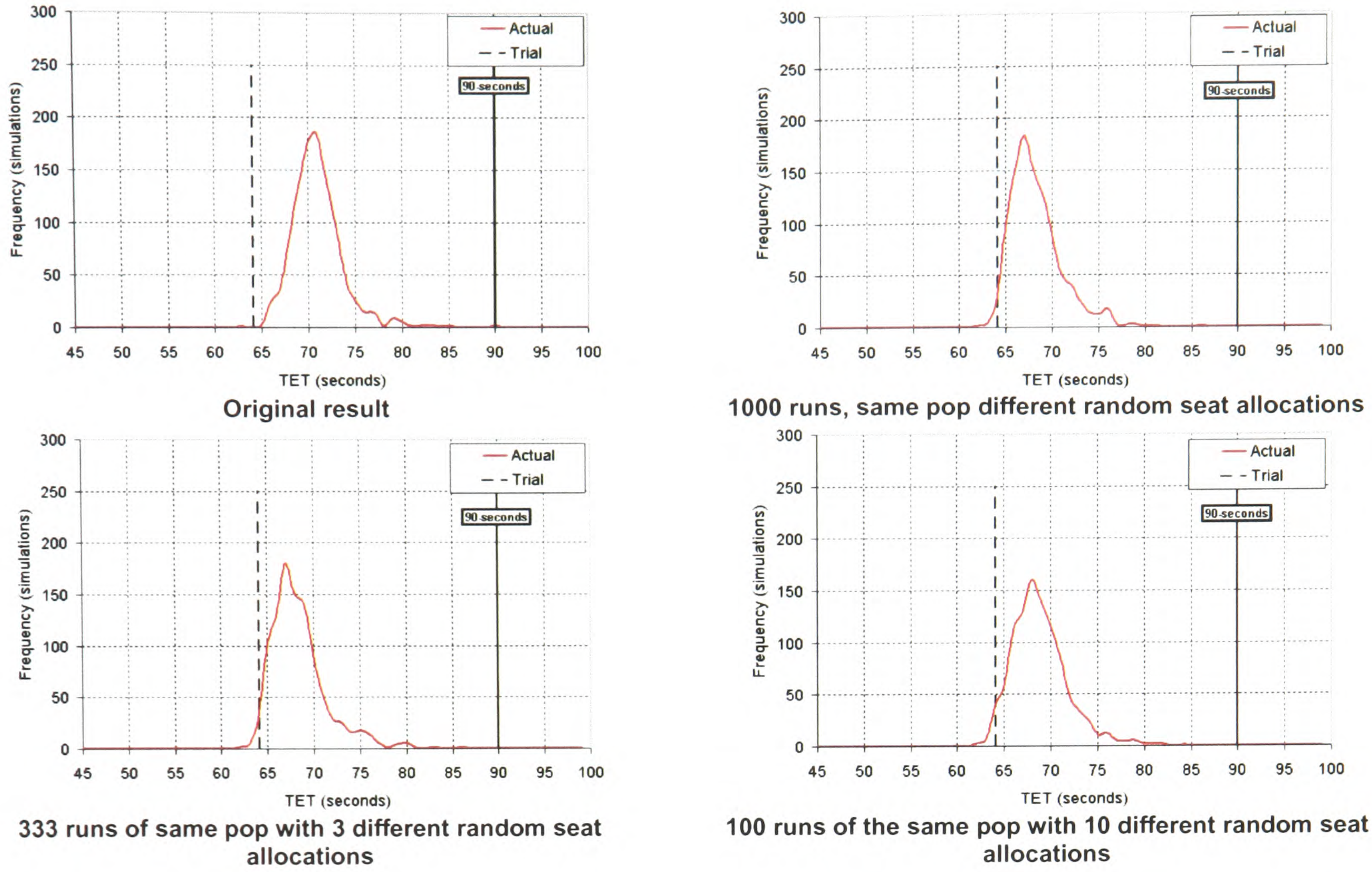


Figure 29: Results of airEXODUS when randomising passenger seating allocations for Case 5 using the Actual data

Furthermore, as can be seen from Figure 30, the numerical window of results better captures the trial curve when a randomisation of seating allocations is used.

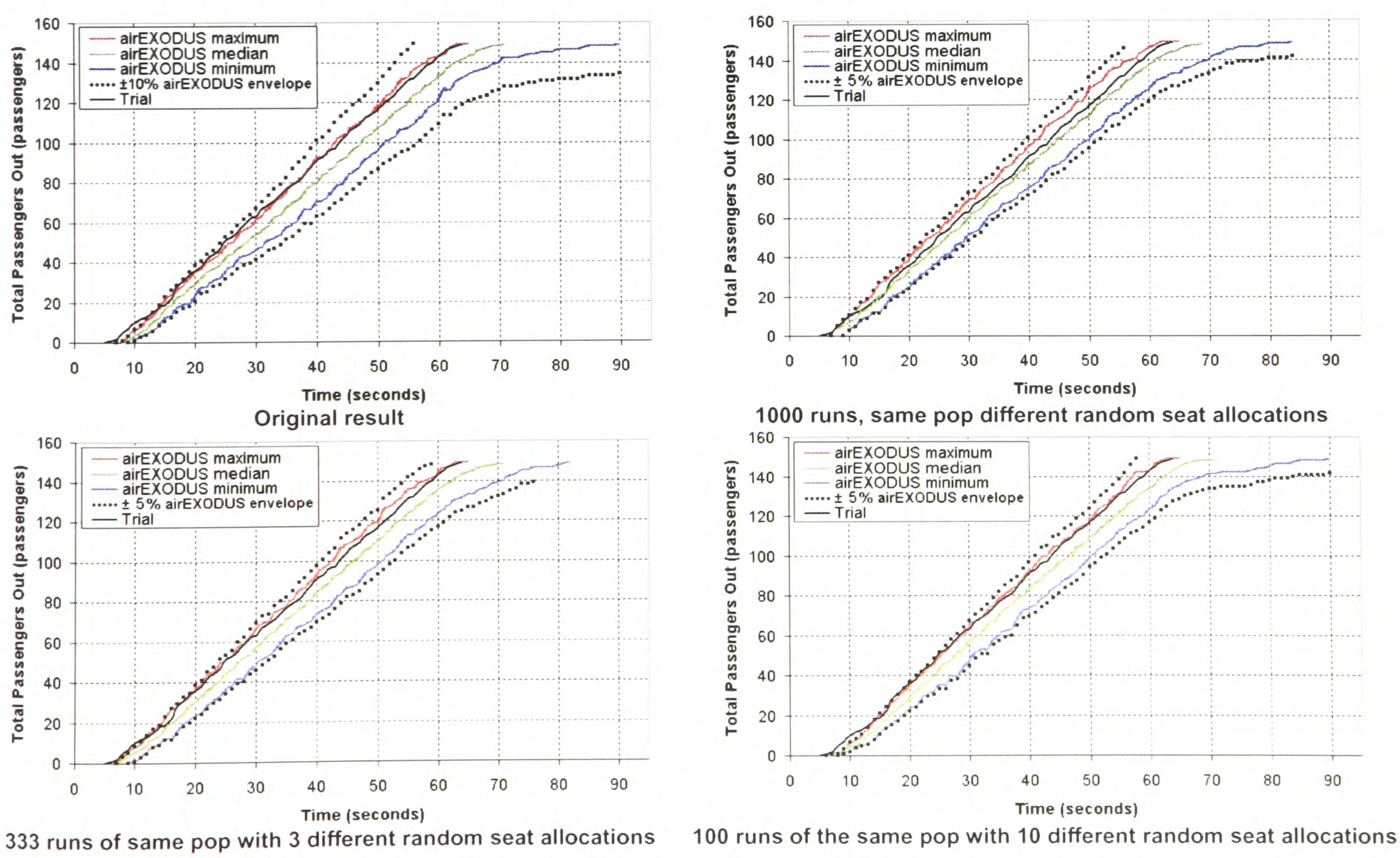


Figure 30: Results of airEXODUS when randomising passenger seating allocations for Case 5 using the Actual data

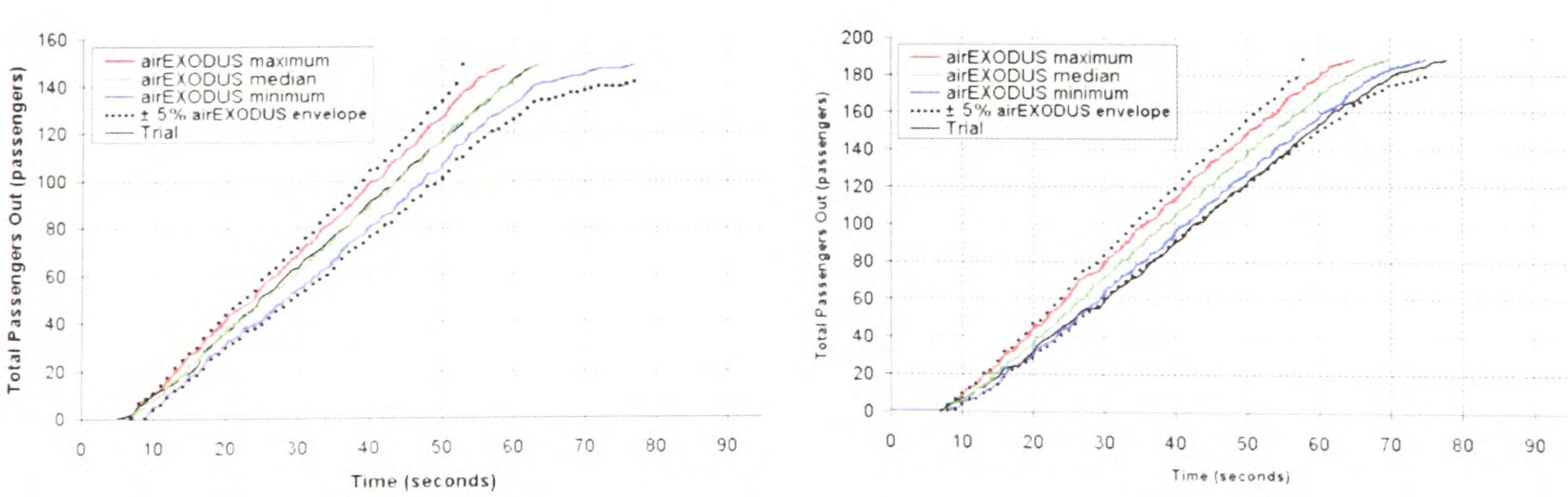
4.5.3.2 Validating the airEXODUS prediction for the evolution of narrow-bodied certification trials using the generalised data

The simulation envelopes generated by airEXODUS for the narrow body aircraft using the generalised data are depicted in Figure 31. It can be seen that in Case 5 the result of the certification trial is within the airEXODUS generated simulation envelope (see Figure 31 (a)) for practically the entire certification trial with the exception of the first few seconds of the evacuation. Thus, when using the generalised data in Case 5 airEXODUS predicts a similar number of evacuees to the certification trial at every second of the evacuation.

The results for Case 6 fall marginally outside of the airEXODUS generated simulation envelope after approximately 30 seconds, but remain within or just exceeds a +/-5% tolerance window (see Figure 31(b)). This is consistent with the observation made earlier that this trial was considerably slower than would normally be expected for this type of aircraft configuration. Thus the results of airEXODUS are expected to be better than the results of the single certification trial.

Table 20: Summary of the result of an airEXODUS sensitivity analysis of the B737-300 to passenger seat location when using the generalised data

		First out (secs)	TET (secs)	CWT (secs)	PET (secs)	OPS
Generalised Data	Min	7.5	59.8	20.4	33.3	0.00
	Mean	**7.7**	**65.0**	**22.6**	**35.7**	**0.05**
	Max	8.9	77.4	24.7	37.8	0.18
	STD	0.2	2.1	0.7	0.7	0.03
Generalised Data (3 random seat locations)	Min	7.5	60.2	20.0	33.0	0.00
	Mean	**7.7**	**65.5**	**22.3**	**35.4**	**0.07**
	Max	8.8	77.4	24.7	37.8	0.18
	STD	0.1	2.1	0.9	0.9	0.03



(a) (b)

Figure 31: The airEXODUS simulation envelopes generated using the generalised data for (a) Case 5 and (b) Case 6

In order to be consistent with the analysis using the actual data, Case 5 was run with several randomisations of the passenger seating allocation. The results are shown in Table 20 and Figure 32.

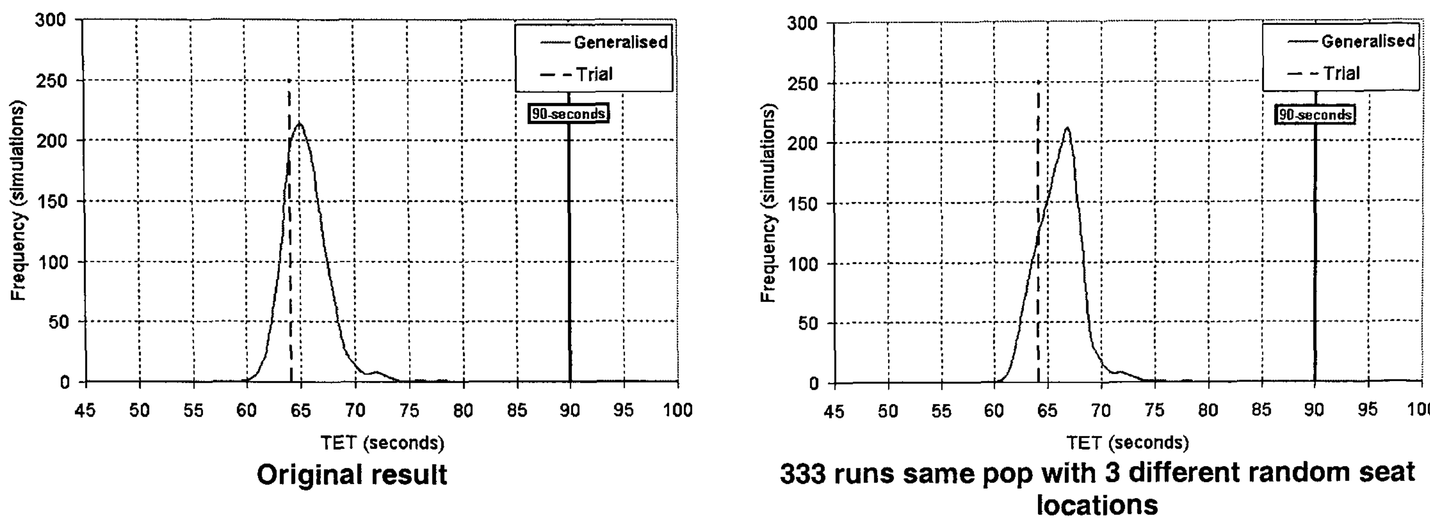


Figure 32: Results of airEXODUS when randomising passenger seating locations for the case 5 using the Generalised data

4.5.4 Summarising the outcome of the airEXODUS reconstructions and predictions for narrow-bodied certification trials

Several key points can be made from the analysis of the two narrow-bodied aircraft validation cases:

1a) Using the actual data from specific certification trails, airEXODUS is able to produce distributions of Total Evacuation Times for each aircraft such that the actual trial data point is contained within the distribution.

1b) Using the generalised certification trial data, airEXODUS was able to predict the distribution of Total Evacuation Times for one of the two aircraft such that the actual trial data point is contained within the distribution. However, the level of optimality as measured by the OPS for the simulation and the trial should be broadly in agreement.

2a) Using the actual data from the specific certification trials, airEXODUS was able to successfully rank the two derivative aircraft in the identical order that was achieved in the certification trials. However, it should be noted that a ranking based on a single certification trial result for each aircraft may not be indicative of the actual ranking of the aircraft.

2b) Using the generalised certification data, airEXODUS was able to successfully rank the two derivative aircraft in the identical order that was achieved in the certification trials.

3a) Using the actual data from the specific certification trials, airEXODUS did not predict the relative and absolute differences between the rank ordering. However, it should be noted that the relative differences between aircraft, like the ranking, based on a single certification trial result for each aircraft may not be indicative of the actual differences between the aircraft.

3b) Using the generalised certification data, airEXODUS did not predict the relative and absolute differences between the rank ordering.

4a) Using the actual data from specific certification trials, airEXODUS predicted that both of the aircraft would pass the certification criterion.

4b) Using the generalised certification data, airEXODUS predicted that both of the aircraft would pass the certification criterion.

5) The cumulative exit curves for each of the two aircraft examined fell within the numerical envelope predicted using airEXODUS and the generalised certification data or only marginally exceeded the envelope (within +/-5%). This suggests that airEXODUS is capable of predicting the time evolution of the evacuation using the generalised data.

6) The observed differences between the simulation predictions and the actual data are thought to be due to the natural variations that occur in specific certification trials. Indeed the two trials that were investigated are believed to be quicker than would normally be expected – for Case 5 – and slower than would be expected – for Case 6 – thus compounding the differences between the model predictions and actual data. However, two points have been noted concerning the use of and further development of the model. In terms of model use, it is important to generate randomisations of the seating allocations of passengers within the sequence of 1000 repeat simulations. In terms of model development, it would be desirable to develop an explicit capability to simulate crew instigated passenger by-pass.

7) For direct comparisons to be made between model predictions and trial results, similar levels of optimality must exist between the model and trial results. When quoting numerical results it is essential to not only quote the times achieved but also the levels of optimality achieved.

Finally, the general conclusions made for the wide-body aircraft apply equally well to the narrow-body aircraft.

4.6 Interpretation of model performance

4.6.1 Use of Generalised and Actual Data.

This work has shown that the same broad conclusions concerning aircraft performance can be derived from simulations utilising the generalised data for exit hesitation times and exit opening times as simulations using the actual data. This suggests that the generalised data represents a good approximation for how key aircraft components will perform under certification applications. This provides the modelling and regulatory community with strong evidence to support the use of the generalised data for aircraft certification applications in which the standard configurations and components are being considered.

This general approach can be extended to situations in which the generalised data is not applicable, for example, when a new or significantly modified aircraft exit type is being used. In this situation, rigorous testing of the exit component is necessary in order to generate the appropriate data to use in the model. This testing should be sufficient to provide data of similar quality to that used to generate the existing generalised data.

4.6.2 Predicted Evacuation Times.

In comparing the model predictions with the trial performance, we are attempting to compare a single experimental data point of a variable known to be defined by a probability distribution i.e. TET, with a predicted probability distribution for the TET. In reality, the TET from the trial could be any point on the probability distribution. In this analysis, we have chosen to compare the trial data point with the mean from the predicted distribution of TETs.

Across the six aircraft studied, using the generalised data, airEXODUS was able to predict the TET on average to within **3.8%** (variation of 0.8 – 11.6 %) or **2.8 seconds** (variation of 0.5 – 11.6 seconds) (see Table 21). When using the actual data, airEXODUS was able to predict the TET on average to within **5.3%** (variation of 3.0 – 10.0 %) or **3.8 seconds** (variation of 2.2 – 6.4 seconds) (see Table 22).

Situations that created the largest error involved cases in which the level of optimality of the trial did not sufficiently match that of the simulation. In these cases larger errors are to be expected as strictly speaking, like is not being compared with like. Effectively, differing levels of optimality should be represented as different scenario specifications. It was also demonstrated that airEXODUS was correctly able to predict the evolution of the evacuation in virtually every case and only in cases where the optimality was borderline there was a slight divergence between measured and model predictions.

Table 21: Summary of Trial and airEXODUS predictions using the generalised data

	Trial evacuation time (Secs)	AirEXODUS mean TET (Secs)	Number of simulations with a similar OPS (Simulations)	airEXODUS mean from trial TET (%)	airEXODUS mean from trial TET (secs)
Case 1	83.7	82.7	1000	1.2	1.0
Case 2	72.6	73.1	1000	0.8	0.5
Case 3	71.7	68.3	1000	4.7	3.4
Case 4	74.4	77.9	1000	2.8	2.1
Case 5	64.1	65.0	1000	1.4	0.9
Case 6	78.5	69.4	1000	11.6	9.1
Average Absolute Error				3.8%	2.8 s

Table 22: Summary of Trial and airEXODUS predictions using the actual data

	Trial evacuation time (Secs)	AirEXODUS mean TET (Secs)	Number of simulations with a similar OPS (Simulations)	airEXODUS mean from trial TET (%)	airEXODUS mean from trial TET (secs)
Case 1	83.7	86.6	1000	3.5	-2.9
Case 2	72.6	70.4	1000	3	2.2
Case 3	71.7	68.2	1000	4.9	3.5
Case 4	74.4	76.9	1000	3.4	-2.5
Case 5	64.1	70.5	1000	10	-6.4
Case 6	78.5	73.0	1000	7	5.5
Average Absolute Error				5.3%	3.8 s

It is recommended that as an indication of the likely error in predicted results, the errors associated with the actual data should be taken as this represents a true indication of the predictive capability of the model.

4.7 Ranking aircraft performance

Using the mean TET from the predicted distribution, it has been shown that airEXODUS was able to correctly rank the performance of the four wide body aircraft and the two narrow body aircraft (see Table 23). However, when the narrow and wide body aircraft were put together and the six aircraft are ranked, we no longer find that the predicted ranking of the aircraft match the ranking observed on the basis of the single certification trial (see Table 23). This is true whether we make use of the actual or generalised data.

As mentioned earlier, it is difficult to attempt an absolute or even relative rank ordering of aircraft performance based on the performance of a single certification trial (or model result). This is because the performance of the aircraft is defined by a probability distribution of which the single data point is not a characteristic measure. Thus there is no guarantee that the ranking derived from the certification trials are typical or indicative of actual relative or absolute performance.

Table 23: Rank ordering of aircraft evacuation performance using the trial data and airEXODUS generated TET using the actual and generalised data

Actual data	Trial evacuation time (Secs)	airEXODUS mean TET (Secs)	Trial wide body rank	airEXODUS wide body rank	Trial narrow body rank	airEXODUS narrow body rank	Overall Trial rank	Overall airEXODUS rank
Case 1	83.7	86.6	4	4	--	--	6	6
Case 2	72.6	70.4	2	2	--	--	3	2
Case 3	71.7	68.2	1	1	--	--	2	1
Case 4	74.4	76.9	3	3	--	--	4	5
Case 5	64.1	70.5	--	--	1	1	1	3
Case 6	78.5	73	---	--	2	2	5	4
Generalised data	**Trial evacuation time (Secs)**	**airEXODUS mean TET (Secs)**	**Trial wide body rank**	**airEXODUS wide body rank**	**Trial narrow body rank**	**airEXODUS narrow body rank**	**Overall Trial rank**	**Overall airEXODUS rank**
Case 1	83.7	82.7	4	4	--	--	6	6
Case 2	72.6	73.1	2	2	--	--	3	4
Case 3	71.7	68.3	1	1	--	--	2	2
Case 4	74.4	77.9	3	3	--	--	4	5
Case 5	64.1	65.0	--	--	1	1	1	1
Case 6	78.5	69.4	---	--	2	2	5	3

As can be seen from Figure 33 if the trials are repeated a sufficient number of times, the TET can be distributed with a large scatter and it is possible for data points for different aircraft to become mixed. In this overlap region it is possible for the rank ordering of aircraft to be altered, depending on which data points are selected at random to represent the aircraft. This can be more clearly seen in Figure 34 that shows the range of TETs generated by airEXODUS for each aircraft.

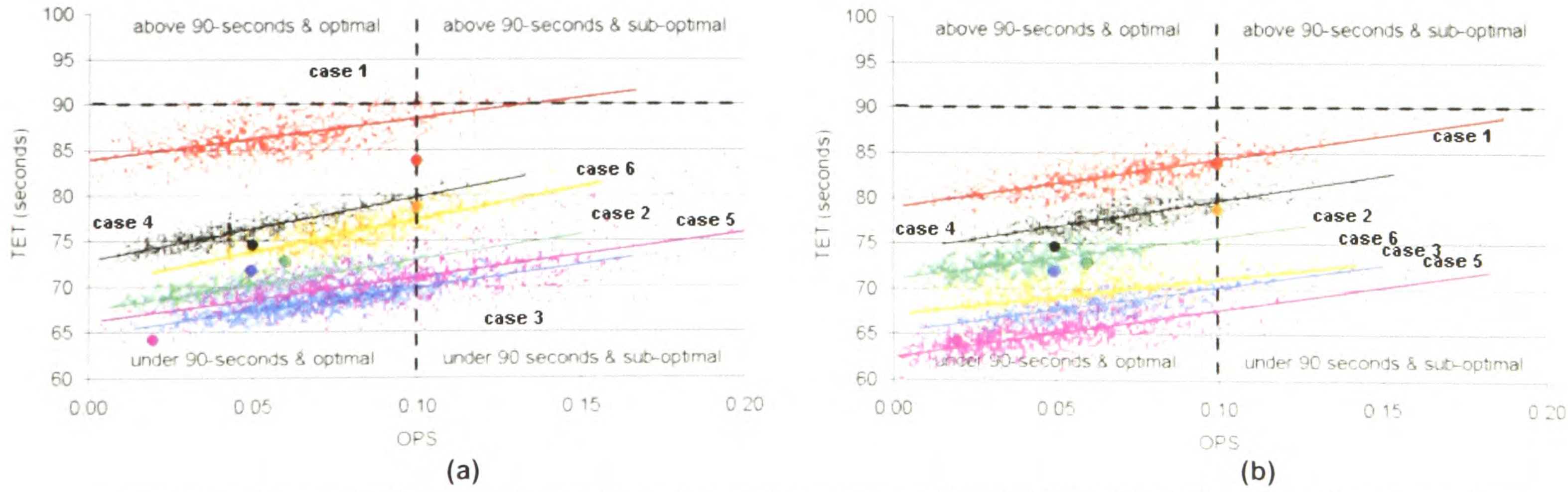


Figure 33: airEXODUS produced scatter plots of TET Vs OPS for the six aircraft generated using (a) actual data and (b) generalised data

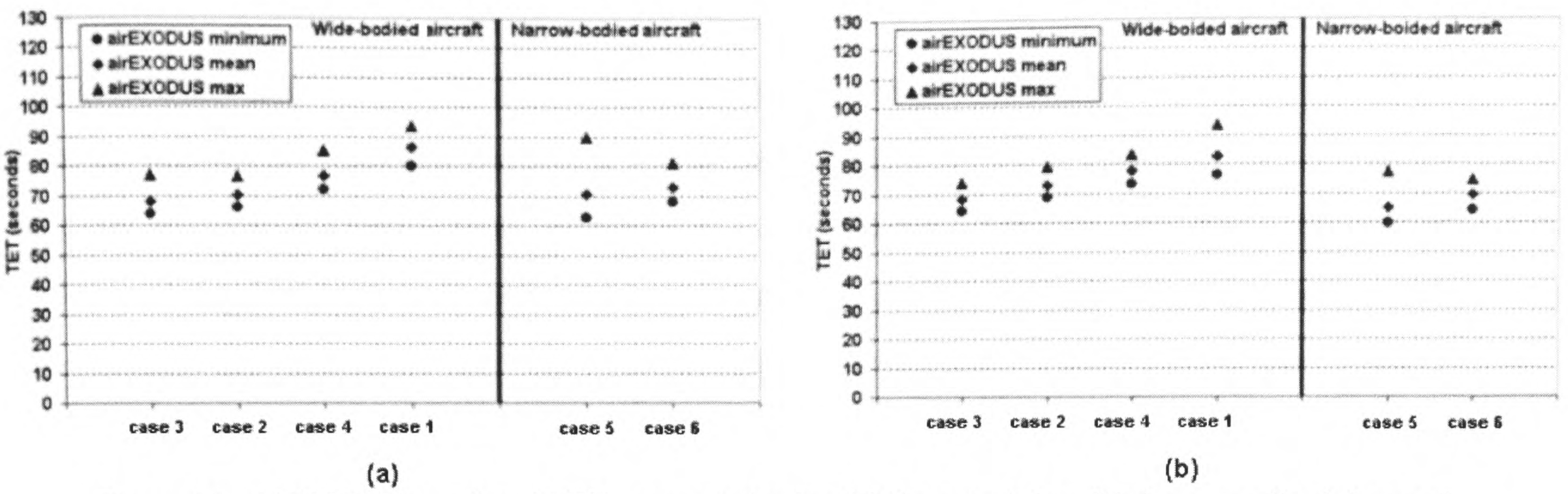


Figure 34: airEXODUS produced TETs generated using (a) the actual data (b) the generalised data and

As can be seen from Figure 33 and Figure 34, in the majority of cases the frequency distribution curves for the various aircraft show some degree of overlap. In cases where overlap occurs it is possible for the ranking of the aircraft to be altered if only a single data point is selected to represent the performance of the aircraft – as is the case in the certification trials. Similarly, in cases where there is no overlap, it is possible to define a definitive ranking.

4.8 Concluding remarks

This chapter has demonstrated how the results of a model can be tested, verified and interpreted through the application of a comprehensive validation exercise. Whilst validation will never prove a model correct, confidence in the models predictive capabilities will be improved the more often it is shown to produce reliable predictions. In this context this chapter has tackled one of the key questions raised in this thesis that blocks the acceptance of evacuation modelling technology in the design and certification of passenger aircraft (see Section 3.14).

This work has added an additional six test cases to the list of validation already undertaken by airEXODUS. These cases have shown that the model is capable of successfully reproducing the overall evacuation performance of both wide-body and narrow-body aircraft under certification conditions. Using the mean of the airEXODUS generated total evacuation time distribution for each aircraft and the single time achieved by the aircraft in each of the trials to represent the typical evacuation performance, airEXODUS is capable of predicting the total evacuation time to within *5.3%* or *3.8 seconds* on average. It was also shown that in most cases the model is able to reliably predict the likely evolution of the evacuation from its start to its completion.

The success of the airEXODUS evacuation model in predicting the outcome of previous 90-second certification trials is a compelling argument of the suitability of this model for evacuation certification applications - at least for derivative aircraft. For aircraft involving truly 'new' features it is expected that evacuation models in conjunction with component testing of the new feature will be necessary. Examples of new features include a new exit type or an established exit configuration placed at a sill height surpassing that previously used. In both these examples it is assumed that sufficient data does not exist that would allow a reliable representation within the evacuation model. In these cases, the combination of computer model and component testing offers a sensible and reliable alternative to full-scale live evacuation trials.

This chapter has also indicated a potential area that needs to be addressed to answer the second key question posed by this thesis, namely, *"How can the results and behavioural capabilities of the model be improved?"* The results of these validation tests demonstrated the lack of an adequate representation of crew procedures and their interactions with passengers. Indeed this is thought to have negatively impacted on the accuracy of the model in these validation exercises. This further strengthens the observation that future work should be directed at developing these capabilities. Indeed this area and others are addressed in the following four chapters.

5 A study of exit choice, seat jumping and aisle swapping behaviour in aircraft evacuations

5.1 Introduction

So far this thesis has demonstrated how evacuation models can be tested.and how confidence can be gained in their use. However, in doing so the requirement for a more realistic representation of **cabin crew procedures** was highlighted. This feeds into the second key question posed in this work, namely *"How can the results and behavioural capabilities of the model be improved?"*. In attempting an answer to this question this chapter poses and answers the following question, *"How important are crew procedures in certifications and real accident situations, is it necessary to model these procedures?"*

Also, recall that Chapter 3 highlighted two other critical areas for model development. They were the absence of passenger aisle swapping behaviour and the simplistic approach to simulating seat climbing behaviour. Before these areas can be addressed their frequency and features require exploration. In this context this chapter poses and attempts an answer to the question, *"How important is seat climbing and aisle swapping behaviours and is it necessary to model them?"*

Before continuing it is important to more accurately specify the processes that have been highlighted for development in this work. The first is referred to as cabin crew redirection procedures. This is a major function of cabin crew during an evacuation and involves them managing the flow of passengers within the cabin and to seek an optimal distribution of passengers to each of the available exits this role is often referred to as passenger flow management or crew initiated redirection. As part of this role cabin crewmembers can redirect passengers away from one exit towards another. The procedure represents an attempt by the crew to expedite a faster evacuation for the aircraft as a whole.

At present aircraft evacuation models do not have an adequate representation of this very important aspect of evacuation. This was recognised in a report by the Office of Technical Assessment for the US congress in 1993 [1], which highlighted the inability of mathematical evacuation assessment models to simulate operator procedures. As such, this section develops a model to represent cabin crew redirection (a vital component of the operator procedure). For the purposes of this work, cabin crew redirection is defined as a procedure in which a cabin crewmember bypasses a passenger from one available exit in a cabin section to another exit in the cabin section in order to bring about a faster evacuation through more efficient exit utilisation. This section analyses 90-second certification trials and air accidents contained within the AASK database V3.0 to build a picture of this behaviour in real emergency evacuations.

In order to model the effectiveness of the procedure in real emergency evacuations it is also necessary to include passenger decision making relating to exit selection, as in real emergencies passengers are actively seeking their own escape routes during an evacuation. The interaction of passenger exit selection and crew exit selection is explored in this chapter.

An extension to the passenger exit choice model is to provide passengers with methods for evaluating and optimising their chosen evacuation route. This thesis primarily focuses on two main route optimisation strategies, namely passenger aisle swapping, and passenger seat climbing.

Aisle swapping refers to passenger(s) choosing to swap to adjacent aisle(s) in the view that it will expedite their evacuation. By definition aisle-swapping behaviour can only occur on aircraft that have multiple aisles. Given that proposed future aircraft designs, such as the BWB, may contain more than two passenger aisles, the significance of this type of behaviour may be of more importance in the future. Seat climbing is a more extreme form of route optimisation that sees the passengers climb over seat backs. This behaviour is frequently cited by researchers performing 'competitive' experimental trials and in air accident reports. This behaviour is also investigated in this chapter.

Before continuing with the investigation it is important to clearly define the behaviour that we are studying. In the context of this work aisle swapping is a behaviour that involves moving from one viable aisle to another viable aisle whilst maintaining the same target exit. By definition, this represents abandoning a **viable** escape path in favour of another **viable** escape path. The term seat climb can describe numerous types of behaviour such as, climbing over a seat to reach a rupture in the cabin, climbing to circumvent a physical blockage, etc. In the context of this work seat climbing is defined as a behaviour that involves a passenger climbing over seating to avoid a particular route based on the locations of other passengers. Situations in which passengers climb seating or swap aisles when the path represents the ONLY viable escape route are excluded as they represent a different type of behaviour that is already covered within the model.

Before any development can take place it is necessary to answer the following questions, *"What evidence can we collect to support the development of these behaviours?"* and *"How can we better understand the processes involved in all of these behaviours, we need to determine?"* To answer these questions a study of human behaviour in aircraft accidents is undertaken in this chapter. In doing so an empirical understanding of the processes involved and their frequency and nature is developed. In addition this study provides insight into the third key question in this thesis, namely, *"How can the behavioural capabilities of the model be extended to cover the range of behaviour witnessed in real accidents scenarios?"*.

5.2 Data on Which to Base a Model

Video footage and crew interview transcripts from 90-second certification trials and survivor accounts from real accidents contained within the AASK database V3.0 were available to the authors for the research of these behaviours. This analysis concentrates first on observed behaviour from 90-second certification trials. This is followed by an analysis of behaviour found in real emergency evacuations.

5.3 Data from 90-second certification trials

Cabin crew instigated redirection is frequently witnessed in 90-second certification trials. As such they represent a rich source of information concerning this behaviour. In addition, 90-second certification trials are recorded on video and most 90-second certification trial reports contain post-evacuation interviews with cabin crewmembers. These are extremely useful for understanding the reasons why cabin crewmembers preformed certain actions. An understanding of crew instigated bypass in 90-second certification trials is developed from the interview transcripts using video footage for support. In contrast, passenger interviews were not included in any of the 90-second certification trial reports. As such understanding passenger behaviour is more difficult. However, scrutiny of 90-second video footage allows some insight into the frequency of certain behaviours as well as the conditions in which the behaviours most frequently occur. This insight can give some tentative understanding of the behaviours in 90-second certification trial conditions.

Finally, the availability and quality of data should be tempered by the knowledge that the behaviour of passengers and crew during certification trials are not representative of the likely behaviours witnessed during real emergency evacuations [1]. Thus, any model that is based upon performance during certification trials is likely to represent the performance of the procedure under essentially optimal conditions. When designing mathematical models of human behaviour it is often useful to begin with a relatively simply set of behaviours which can later be extended to encompass more scenarios. In this respect, 90-second certification trials offer an ideal initial starting point for a mathematical model of cabin crew instigated redirection. This analysis therefore begins with behaviour during 90-second certification trials.

5.3.1 Developing an understanding of crew redirection based on data from 90-second certification trials

This section discusses behaviour from video footage of 90-second certification trials and verbatim post-evacuation transcripts of cabin crew interviews. The purpose of the discussion is to describe the process and to highlight the salient features that a prototype model should contain.

It was evident from video footage of 22 certification trials that crew directed bypass occurs relatively frequently during 90-second certification trials. This is not surprising as crew are briefed on the manufacturer's procedures for the aircraft prior to the 90-second certification trial taking place. During these evacuations, they are acutely aware of the possible requirement for the procedure during the evacuation.

From examination of video evidence it is apparent that a pair of floor level exits usually have two cabin crew stationed within their vicinity that operate as a team during the evacuation [90]. Since the exit availability criterion of 50% is always met by disabling one exit from each exit pair, typically one of the cabin crew occupies the DAS

(Dedicated Assistance Space) and motivates passengers onto the escape slide whilst the other takes responsibility for motivating passengers to the exits and redirect passengers within the cabin.

Video evidence from 90-second certification trials strongly suggests that crewmembers whose duty is motivating passengers onto slides are very rarely involved in passenger redirection [90]. In general they are too preoccupied with motivating passengers onto the escape slides. From video evidence it was apparent that it was sometimes the duty of the flight crew to assist the cabin crew in directing the flow of passengers within the cabin. However, this practice was only evident in early certification trials and has for some years not been required within flight crew evacuation procedures. Thus, in future they would not be involved in redirection during certification trials.

Manufacturer procedures nearly always designate specific locations on the aircraft that cabin crewmembers should occupy in order to supervise the flow of passengers throughout the cabin. This was apparent from examination of 90-second certification trial documentation in which cabin crew training materials were enclosed. On any given aircraft these positions can be located close to their jump seat or some distance away. If the location is some distance away the cabin crewmember may have to negotiate a path through the cabin. It was therefore necessary to re-examine video footage of trials in order to determine any inherent difficulties in reaching their assigned station. The video footage suggests that cabin crew are able to move through aisles - albeit more slowly than when the cabin is empty - even when the aisles are packed with passengers. During their movement they typically shout instructions for passengers to move out of the way. Sometimes crew member resorted to climbing over seats to avoid confluence with passengers in the aisles.

Whilst during the early portion of evacuations cabin crew can generally move to their designated areas within the cabin, they do sometimes experience difficulties when moving through congested aisles to reach over wing exits. This was highlighted within the post evacuation interviews from certification trials. As an example the First Officer from the certification trial of a narrow bodied aircraft described some difficulty in moving to the overwing exit thus, *"My progress, I think, just about stopped. With lots of yelling, some people moved out of the way and some didn't." [90]*

Similar difficulties were stated by the captain when moving from the cockpit to centrally located exits during the evacuation of another narrow bodied aircraft,

"... it was very difficult to get through because by then the people were crowding the aisle, at which time I yelled as loud as I could to tell them that I had to get through." [90]

However, whilst difficulties were cited in post evacuation interviews and observed on video footage the passengers are rarely completely obstructive to the crew. Typically, a shouted instruction or a push is sufficient for the passenger(s) to give way. As another cabin crewmember stated after the evacuation of another aircraft,

"He [the captain] yelled to the passengers, 'Let me through,' and the passengers were very cooperative and let him through." [90]

Given these difficulties, a requirement of a prototype model is that the movement of crewmembers is explicitly modelled. In addition, a method imposing some movement penalty when moving against the flow of passengers should be incorporated.

Once the cabin crewmember has reached their designated position within the cabin they typically begin to monitor proceedings and try to ensure that all of the exits finish evacuating passengers at approximately the same time. At this point the cabin crew begins to implement flow management procedures.

Table 24: Relevant quotations found in 90-second certification trial interviews

Nature of cabin crew quotation found within 90-second certification trial reports	Number of quotations
An instance of redirection only	6
Rationale for redirecting	8
Movement within the cabin	7
Visibility within the cabin	7
The method of commanding passengers	7
Their effectiveness at persuading passengers	5
Total relevant quotations	40

In order to develop a model, it is necessary to understand the thought process of the cabin crewmember during this period (or at least the behavioural manifestations of these processes). It is necessary to determine how they decide when to redirect passengers and how they obtain information upon which their decisions are based. In order to answer this, post-evacuation interviews were examined to understand the crewmembers' reasons for redirecting passengers and their methods of gathering information. In total 40 relevant and potentially useable references were made with respect to redirection during 90-second certification trials (see Table 24). Given the large number of quotations it is not feasible to include them all in this work. However, some representative quotations that encapsulate the features of their category are provided within this discussion.

During the post certification trial interview of the a wide-bodied aircraft a crewmember described his rationale for redirecting passengers to another exit. The crew was stationed at the 2LL exit and was managing the flow within the cabin as his exit was inoperable. He stated that,

CABIN CREWMEMBER: There was actually a clump of people waiting to exit from Door 2 right. I looked up and noticed that Door 1 was cleared, virtually cleared. There was only a couple of people waiting to go, so I just took judgement to actually send them up front to Door 1 left" [90]

A crew involved in another wide-bodied 90-second certification trial was again responsible for cabin management as his exit (3R) was inoperable. He described his rationale thus,

"QUESTIONER: Can you explain how you decided where you were going to redirect people to go?
CABIN CREWMEMBER: I knew that the slide to the back would accommodate more people than ours...
QUESTIONER: But door 2 also is a Type A door and has more capability, but you decided not to send people toward Door 2.
CABIN CREWMEMBER: Well, yeah, but door 2 also had a large line as well..." [90]

These two examples, encompass the content of many more extracts that were found within cabin crew interviews and suggest a rationale for crew redirection. Crew appear to make a determination on the likely finish time of the exits in their vicinity and attempt to fix any imbalance via redirecting passengers. It appears that information is central to their making judgements, i.e. information of: the location of exits, the exits for which the cabin crewmember is responsible, knowledge of useable exits, the number of passengers that are using particular exits, the current flow pattern within the cabin section, and the flow rate capabilities of the individual exits. Whilst not definitive, this list gives some indication of the likely factors that cabin crewmembers would consider when managing the flow of passengers. This information can be categorised as either dynamic or static.

Dynamic information is gained during the evacuation itself and is subject to change during the evacuation. For example, the location of passengers within the aircraft cabin at a particular point in time, active exits onboard the aircraft, flow pattern through the cabin section, flow rates that are being achieved at each exit, etc, are all dynamic information. Static information does not change during an evacuation. For example, the configuration of the aircraft, locations of exits, exits for which a cabin crewmember has responsibility, relative differences in likely flow rates, etc, are all static information.

By definition dynamic information must be collected during the evacuation. From the analysis of video footage of certification trials and interviews of the crew, it is apparent that crew typically collect dynamic information visually. For example, the cabin crew stationed at the 4L during the certification trial of a narrow-bodied aircraft stated,

*"...I **noticed** [emphasis added] that the windows were clearing out [the over wing exits], and it was still a slow single line movement down to the back doors. I redirected some people back to the window exits..."[90]*

The first officer on board the same aircraft was also involved in redirection activities. He stated a similar method of obtaining information. He stated that,

*"... I turned around and **noticed** [emphasis added] that door two was vacant [free from passengers]..."[90]*

Indeed vision was also frequently stated as the means that cabin crew determined useable exits during the evacuation. As the account of the FL cabin crew during the post evacuation interview of a wide bodied aircraft certification trial demonstrates,

"... from where I was standing I was aware that 1 left and 2 right were definitely operating. From there it was difficult to see. It was just heads everywhere." [90]

Again, these extracts are illustrative of numerous similar accounts and indicate that a requirement of the prototype model is to have a mechanism of representing passenger vision that affects the gathering of dynamic information during the evacuation.

Another finding of this study was that instances of cabin crewmembers verbally communicating dynamic information were rare. Indeed when communication occurs, video evidences strongly suggest that it is between the crew and is regarding the cabin sweep, i.e. the determination of whether the cabin is clear of passengers. As such it invariably occurs once the majority of passengers have evacuated. During the period when redirection is most likely, i.e. during the mid portion of the evacuation, video footage and interview transcripts suggest that verbal communication between cabin crew is extremely rare.

From further examination of crew interview transcripts it appeared that the level of visibility varied according to the location and capabilities of the cabin crewmember. For example, whilst the cabin crewmember stationed at the 3R exit during the 90-second trial of a wide-bodied aircraft stated,

"... it surprised me to be able to see so far. I had a very good idea of what was going on pretty much on the whole aircraft, I feel." [90]

His colleague at the 4R exit stated the opposite. He stated that,

"I wasn't able to see far down as 3 right because, as I say, the passengers were coming towards me so I wasn't able to see over the passengers." [90]

Indeed the level of visibility is affected by numerous interacting factors, such as the height of the crewmember, the level of lighting, the visual accessibility of the structure, the height of passengers, the presence of bulkheads or monuments, the location of the crewmember, to name but a few. This suggests a further requirement of a prototype model is that it contains a mechanism for defining individual levels of visibility for each crewmember/station within the aircraft cabin.

The final aspect of redirection examined was the method employed when communicating their instructions to the passengers. Video footage of certification trials suggested that cabin crew use either, verbal commands (shouting, speech, etc), gestures (pointing, waving arms), physical contact (manhandling, pushing in a direction) or sometimes a combination of these methods. Some crew described their method of communication in post evacuation interviews. For example, one crewmember stated that,

" ...[I] started grabbing people and shouting at them and pushing them towards the exit." [90]

Whilst a first officer from a different aircraft evacuation described a similar approach,

"... All the passengers would have exited the aft hatch had I not physically grabbed them and pushed them through between the seats to the forward hatch..." [90]

From the interviews of cabin crewmembers it is apparent that they generally perceive physical communication to be a more effective means of asserting their will than merely shouting. As the following example demonstrates, another observation was that for some crew shouting was deemed enough motivation to persuade passengers to redirect,

"QUESTIONER: Did you have any problems in motivating passengers forward past your exit up the right-hand aisle?
CABIN CREWMEMBER: No, none at all. I shouted "Faster! Faster! Go this way faster!" and they did very quickly" [90]

In general video evidence indicated that cabin crew are generally very successful at enforcing their commands. Indeed, interview transcripts indicate that passengers appear to be very receptive and cooperative in response to cabin crew commands. For example passengers ask polite questions to the crew, such as "*Can I use your exit?*" [90 or "*...are we all going to have to go out that door?*" [90]. Certainly cabin crew perceive their actions as being very effective during 90-second certification trials. For example, a crew member in a narrow-bodied aircraft trial described their redirection experience thus, *"I had to turn around and tell everyone to, 'turn around! Go that way!' a couple of times, and everyone seemed to be following directions pretty well. ... everyone was very cooperative, obeyed commands, ..."[90]*

A similar statement was made by the 4R cabin crew during the certification trial of a wide-bodied aircraft, who stated that,

"The passengers seemed to understand instructions that we gave them, and they responded accordingly."[90]

From this it is apparent that a requirement for the prototype model is that it represents the two principle modes of cabin crew communication, i.e. verbal/gesture and physical. Furthermore, it would be desirable that the model should have a mechanism for representing difference in communication ability and a level of passenger receptiveness to their commands.

5.3.2 Conclusions

To summarise, from the analysis of video footage it is apparent that cabin crew redirection occurs frequently during certification trials. In performing redirection the cabin crewmembers have to travel to a designated location within the aircraft cabin interior to perform their management duties. Video evidence and anecdotes from cabin crewmembers indicate that they are generally able to achieve this. However their movement speed is sometimes hindered by the presence of passengers.

Once at their station cabin crewmembers begin to monitor the flow of passengers in the aircraft. Generally this involves the cabin crew assessing local factors and switching passengers to other exits where necessary. Vision is the primary mechanism that they use in determining conditions within the cabin. This is affected by their own abilities and the configuration of the cabin. Thus, a model should represent individual visibility levels for crew.

Having determined that redirection is required they must communicate commands to passengers. Video and anecdotal evidence suggests that cabin crewmembers are highly effective at transmitting commands to passengers during 90-second certification trials and that the passengers are very co-operative. A mechanism of representing crew-passenger communication is also a requirement of any model.

5.3.3 Developing an understanding of aisle swapping behaviour from observations of 90-second certification trials

In total, video footage was available from 13 wide-bodied certification trials. Video footage of one entire aircraft series was not of sufficient quality to allow even qualitative observations of behaviour within the seating zones. However, the video footage of nine aircraft all contained acceptable camera angles of the cabin interiors. A brief summary of aisle swapping related behaviour present within the video footage of these aircraft certification trials now follows. It should be noted that the numbering scheme used in this section is different to that used in the validation study in Chapter 4.

(i) Trial 1

Examination of the seating zones during the evacuation of trial 1 indicated that aisle swapping did not occur.

(ii) Trial 2

The video footage of trial 2 contained camera shots of two passenger zones. No passenger initiated aisle swapping was witnessed from the video footage of these zones. However, some instances of the flight crew ordering passengers (between 4 and 5 passengers) to switch aisles was evident.

(iii) Trial 3, 351 passengers

The video footage of trial 3 contained camera angles of three passenger zones. No passengers swapped to the empty near aisle. In zone two, aisle swapping was not witnessed. In zone three, a single passenger swapped to the back of the near aisle queue.

(iv) Trial 4

Video footage of three passenger zones were available from the video of trial 4. No passengers in the forward zone swapped to the far aisle. In zone two, over 30 passengers swapped aisles. Some of these (approximately five) swapped into the mid-portion of the queue. Many of these passengers later swapped back to the aisle from which they had originated. The majority of passengers swapped aisles to the back of queues. In zone three approximately seven passengers swapped to the back of the near aisle queue.

(v) Trial 5

Video footage from another three passenger seating zones were available of trial 5. In zone one, some 30 or so passengers were redirected forwards using the far aisle. The 20th from last passenger slipped in the aisle causing a delay to those behind. Five of those passengers that were behind switched to the near aisle.

In zone two, approximately 14 passengers swapped from the far aisle to the back of the near aisle. In the third zone two passengers swapped to the back of the near aisle queue. Later another passenger – the last person in the far aisle queue - swapped to the virtually empty near aisle.

(vi)Trial 6

Video footage of three more cabin zones was available from the certification trial of trial 6. In the first zone, one passenger swapped to the back of the far aisle queue. Later some 40 passengers were redirected by the crew to the forward exits via the near aisle. During this period the far aisle was empty, save two passengers who were redirected forwards via the far aisle. After 25 seconds of the aisle being empty, a passenger swapped aisles. Subsequently three others followed his lead.

In zone two approximately 12 passengers swapped to, what was essentially, the back of the far aisle queue, some of these swapped from within seating. In the same zone, a very fast moving flow of passengers was bypassed aftwards. Approximately 5-10 passengers swapped from the near aisle to the far aisle queue. Most aisle swapping occurred at the back of the far aisle queue, although one or two passengers swapped into the mid-portion of the far aisle queue. Towards the end of the evacuation, 5 passengers switched to the back of the near aisle.

In zone three approximately 15 passengers swapped to the back of the far aisle. At the same time the cabin crewmember at the mid-section exit began to bypass passengers to the aft exit using the far aisle. During this period the near aisle cleared of passengers and was completely empty for some time. After the near aisle had been completely empty for approximately 5 seconds, 14 of the bypassed passengers swapped to the near aisle.

(vii) Trial 7

Video footage of trial 7 was of lower quality than other certification trials. Camera angles were more limited and did not show much of the seating within the zones. As such making determinations as to whether aisle swapping even occurred was extremely difficult. Of the camera angles that were examined, no passenger initiated aisle swapping was observed, although in zone one the cabin crew switched passengers from the far aisle to the near aisle through seating adjacent to the exit

(viii) Trial 8

Video footage of trial 8 was also of poor quality. Camera shots were limited to two internal shots. One was from the aft cross aisle looking forwards the entire length of the aircraft and the other was of the last 10 rows of seating in the aircraft. None of the camera shots gave a view of the forward cabin zone. From the footage of the aft seating it was observed that approximately 3 passengers swapped from the aft far aisle to the near aisle. The aisle swapping occurred relatively early during the evacuation and was into the middle of the aisle queues.

(iix) Trial 9

Video footage of the trial 9 was taken using the same camera set-up as that of trial 8. Using the two camera angles, aisle-swapping events were observed in the aft cabin zone. Some 13 passengers swapped from the near aisle to the back of the far aisle queue. Later, one passenger swapped from the far aisle into the mid-portion of the near aisle. A gap may have developed on account of a passenger falling in the near aisle.

5.3.3.1 Conclusions

Aisle swapping occurred in 6 of the 9 evacuations from wide bodied aircraft during 90-second certification trials (see Table 25). Approximately 130 passengers (4.2%) from the total number of 3047 swapped aisles. It appears that instances of aisle swapping are relatively low when considering the total number of passengers on the aircraft. Having scrutinised video footage some tentative conclusions can be drawn.

Firstly, it appears that despite some evacuations sharing similar circumstances aisle swapping does not necessarily occur. The notable example of this was that aisle swapping did not occur in zone one of trial 4 despite conditions being similar to those in other aircraft in which aisle swapping occurred. In addition, it was rare for only a single passenger to swap aisles. It appears that once an initial passenger decides to swap aisles, others tend to follow. There was also some evidence of passengers choosing to swap to an aisle and then swapping back again.

An important observation from the video footage was that passengers only seem to swap aisles when an opposite aisle is relatively free from other passengers (see Table 25). Thus, it tends to occur late during the evacuation process and usually involves passengers joining the back of the queues (see Table 25).

The implication of this observation is that for most of the evacuation aisle swapping is simply not an option as the path to an alternative aisle may be blocked by other passengers. Indeed this is true for much of the total evacuation time. Furthermore, if the alternative aisle is densely packed then it would be difficult to enter another aisle and so again aisle swapping would not be very attractive – 'why having entered an aisle would you leave it only to have to do it all over again?'. These two conditions prevail for most of the evacuation time.

As such only a small percentage of the passenger compliment are exposed to conditions in which aisle swapping is a viable option, i.e. when the alternative aisle is lightly packed and the seating to the aisle is clear. Thus it may be unwise to give too much credence to the frequency of occurrence expressed as a percentage of the entire passenger compliment, i.e 4.2%. Perhaps a more meaningful statistic is that in 11 out of 20 cabin zones (e.g. 55%) some aisle swapping was witnessed.

Table 25: Summary of aisle swapping in 90-second certification trials

Certification trial	Seating zone	Observed aisle swapping	Condition of adjacent aisle
Trial 1	Zone 1	None	The same
Trial 1	Zone 2	None	The same
Trial 2	Zone 1	None	The same
Trial 2	Zone 2	None	The same
Trial 3	Zone 1	None	Near was empty 15 seconds earlier than far
Trial 3	Zone 2	None	The same
Trial 3	Zone 3	None	The same
Trial 4	Zone 1	None	Far aisle finished 10 second early
Trial 4	Zone 2	30 swapped to near aisle – some swapped back again	Slightly less dense
Trial 4	Zone 3	7 passengers to the back of the near aisle queue	Near aisle finished first
Trial 5	Zone 1	5 to the back of the near aisle queue	Near aisle was empty
Trial 6	Zone 2	14 passengers to the back of the near aisle queue	Near aisle emptied first
Trial 6	Zone 3	3 to the back of the near aisle queue	Near less dense than far aisle
Trial 7	Zone 1	5 to the back of the far aisle queue or empty aisle	Far aisle emptied first
Trial 7	Zone 2	12 to the back of the far aisle queue then 5-10 more	Far aisle was less dense then empty
Trial 7	Zone 3	15 to the back of the far aisle then 14 bypassed passengers	Far aisle was empty first then completely empty
Trial 8	All zones	Insufficient data	Insufficient data
Trial 8	All zones	3 to the near aisle, although poor quality footage	Same (poor quality footage)
Trial 9	All zones	13 to back of far aisle queue	Passenger may have fallen in aisle (poor quality footage)
Trial 9	All zones	1 into near	Contained passengers (poor quality footage)

From these general observations the following aspects need to be incorporated into an aisle-swapping model:

A) when aisle swapping is a viable option it occurs with reasonable frequency,

B) a mechanism that represents the likelihood of a given passenger choosing to aisle swap should be developed,

C) any mechanism should result in the first aisle swap being less likely than any subsequent aisle swap events,

D) passengers should only swap aisles if the adjacent aisle is relatively sparsely populated. This is concerned mainly with the area immediately adjacent to their aisle.

5.3.4 Seat climbing observations from 90-second certification trials

Instances of seat jumping during 90-second certification trials are extremely rare. Examination of the video footage available at FSEG revealed only one instance of a single individual climbing over seats during the certification trial of a wide-bodied aircraft evacuation. As such the development of a model for seat jumping cannot benefit from the relatively good quality observational data from 90-second certification trials.

5.4 Data from real emergency evacuations

This section examines crew bypass, passenger aisle swapping and redirection in actual emergency evacuations. It is widely acknowledged that in actual emergency evacuations passenger motivation is different to that in 90-second certification trials [122,128], thus making cabin management procedures more difficult to enforce in real emergencies. In addition, the presence of a thermo-toxic atmosphere can also affect the physiology and psychology of crew and passengers during an actual evacuation affecting their ability to obtain information and inhibiting the execution of cabin management procedures. Likewise increased stress levels may lead to differences in behaviour that must be examined [171].

5.4.1 The principal effects of fire

The presence of fire and toxic products within the aircraft cabin can affect the physiology of both passengers and crew. Since, this work is concerned only with those effects that impact upon cabin management procedure the most relevant physiological effects are those that impair vision, vocal communication or movement capabilities.

The presence of smoke particulate within the atmosphere reduces the range of visibility of both crew and passengers [89,146]. Primarily this occurs through the opacity of smoke particulate limiting visibility. For example, one surviving cabin crewmember from the emergency landing and evacuation of Air Canada Flight 797, a McDonnell Douglas DC-9-32, at greater Cincinnati International Airport on 2nd June 1983 stated that *"Cabin visibility was impossible due to black smoke."* [20].

In addition to a reduction in visibility, chemical effects from irritant and acidic gases can also affect crew and passengers sight [89,88,10]. As an example, the Human Factors report of the Boeing 737-236 at Manchester International airport on 22 August 1985 stated that survivors eyes were "frosted over" [10]; a known reaction of the eyes to irritant acidic gases. Chemically induced visual impairment during an aircraft emergency evacuation involving fire occurs primarily from the effects of acidic and/or irritant smoke, such as hydrogen chloride or sulphur dioxide [88, 89].

Loss of vision has implications on the movement capabilities of passengers. In extremely dense conditions passengers are limited to tactile spatial awareness, as in the

Manchester accident. This would severely reduce their movement capabilities. This has been documented in non-aviation specific research performed by Jin in 1977 (see Section 2.4.3.3).

In addition to difficulties seeing, the presence of a fire atmosphere can also affect the vocal ability of cabin crewmembers and passengers [134,10]. This results from physiological reactions to heat, toxic products and chemical reactions that can induce respiratory tract pain and difficulty in breathing [88,89]. For example, the presence of toxic gases can induce a contraction of the throat (laryngopasm), a contraction of the lungs (bronchospasm), wheezing, coughing, pain to mention but a few [10, 167]. Medical questionnaires submitted by 12 survivors of the Manchester disaster who were exposed to thick black smoke revealed that 9 had experienced bronchospasm, as well as other toxic related affects such as coughing or wheezing [10, 167]. The net result of exposure to toxic gases is that the ability to communicate vocally is severely reduced [10,99,134]. In reporting the accounts of evacuees from the United Airlines Boeing 727 at Salt Lake city in 1965, Snow reported that:

"... the early effects of the dense, acrid smoke that rapidly filled the cabin was to cut short any attempts to vocalise and many passengers stated that after a breath or two they could no longer breathe or utter any sound. ... Passengers recalled that after a few initial shouts and cries the cabin suddenly became quiet with the only sounds coming from the flames and the muffled efforts of passengers struggling towards the exits." [99]

Both passengers and cabin crewmembers accounts from other accidents corroborate this conclusion. For example, a cabin crewmember from the Manchester accident [10] stated that *"I could not shout due to smoke inhalation."* [166]. During the same accident passengers cited similar experiences, for example the accident investigation stated that:

"A survivor recalled that the heavy smoke atmosphere appeared to 'blanket' sound within the cabin, an effect that has been confirmed by Fire Service personnel from their general experience. In addition it is also apparent that the effect of such an

atmosphere is to rapidly suppress any ability of those affected to shout, due to respiratory and acidic gas 'burning' effects on their throats."[166]

Finally, in addition to the presence of smoke, heat and toxic gases can force passengers to crawl in order to avoid contacting the worst thermo-toxic hazard contained within the cabin. Again this would have the effect of reducing passenger movement capabilities.

In addition to physical reactions to fire, the psychology of passengers and crew during a real emergency evacuation is also likely to be different from that of 90-second certification trials [122]. Whilst it is widely acknowledged that the presence of fire with the perceived threat of injury or death can cause psychological differences to be more pronounced [122, 168], even without a fire, failures in emergency lighting, smoke, impact injury and general stress are likely to result in differences in passenger and crew behaviour.

The aims and motivation of evacuees are likely to be different in real emergency evacuations as compared with 'mock' evacuations, such as the 90-second certification trial. For example, it is recognised by all of the participants that the aim of a 90-second certification trial is to evacuate the entire aircraft as quickly as possible. By contrast during real emergency evacuations the aim of each passengers is to get themselves, and others with whom they are emotionally attached out of the aircraft as quickly as possible. This difference in aims and motivation can lead to differences in observed behaviours [5,6,7].

5.4.2 Defining a suitable dataset for analysis

Given these potential differences, it was necessary to examine data sources from real emergency accidents. The AASK database V3.0 contains the testimonies of passengers and crew from 55 real emergency evacuations. The data contained within AASK has been interrogated in order to develop an understanding of cabin management procedures and passenger route optimisation in real emergency accidents.

5.4.2.1 Available data concerning redirection and exit choice

Testimonies that describe redirection events are present in 27 of the 55 accidents contained within the database. A useful analysis could only be achieved given sufficient data within the database. In seven of the 27 accidents there was insufficient data for a meaningful analysis of the cabin management procedures. For example, the description of a redirection event may have been limited to the simple statement "I redirected". These accounts were discarded from this analysis. This left 20 candidate accidents for investigation. The revised dataset contained accidents involving fires, ruptures and water evacuations. In rupture scenarios a severe impact force can cause seating sections to warp and cabin fittings such as overhead stowage bins can be demolished. As such the movement of passengers within the cabin and the cabin management procedures are likely to be very different to situations with ruptures. Furthermore, those accidents that involve comprehensive structural damage such that passengers are trapped within debris and unable to move are beyond the scope of this study. However, accidents with more minor ruptures provide additional information on cabin crewmember control during emergency evacuations. As such some of these scenarios were investigated.

Table 26: The exit choice and redirection accident dataset for investigation selected from AASK V3.0 (shaded rows are accidents involving cabin burn through)

#	Accident Location	Date	Fuselage Condition (intact / ruptured)	Cabin Smoke (light / severe)	Fire description (minor/major/ internal/external)	Testimony Source (Passengers/ Crew)
1	LaGUARDIA A/P NY	02 March 1994	Intact	None	None	CREW
2	CHARLOTTE DOUGLAS INT A/P, NC	25 October 1986	Intact	None	None	CREW
3	MANCHESTER A/P ENGLAND	08 March 1998	Intact	None	Minor external only	BOTH
4	DALLAS/FORT WORTH INT A/P TEXAS	14 April 1993	Intact	Light	Minor external	BOTH
5	JOHN F. KENNEDY INT A/P	30 July 1992	Intact	Severe	Major Burn-through	BOTH
6	LOS ANGELES INT A/P	01 February 1991	Intact	Severe	Major Burn-through	BOTH
7	DETROIT METRO A/P, MICHIGAN	03 December 1990	Intact	Severe	Major Burn-through	BOTH
8	MANCHESTER A/P ENGLAND	22 August 1985	Intact	Severe	Major Burn-through	BOTH
9	DALLAS/FORT WORTH INT A/P TEXAS	31 August 1988	Ruptured	Severe	Major Burn-through	PASSENGERS
10	GREATER CINCINNATI INT A/P, KENTUCKY	02 June 1983	Intact	Severe	Major internal	BOTH

The motivation and behaviour of passengers and crew during scenarios where the aircraft comes to rest in water are very different to that of land evacuation scenarios. In these types of evacuation behaviour is confused as passenger and crew find it difficult to decide whether to evacuate or wait to be rescued in the comparatively dry aircraft. In addition, delays preparing slides and rafts all serve to make these types of evacuations unique. Given their abnormality when compared with land based evacuations, they are not considered in this analysis.

The dataset was then filtered to remove scenarios that involved severe rupture(s) and cabin deformation. Finally, the aircraft had to be of sufficient size to allow redirection to occur. The final dataset for investigation contained 10 accidents (see Table 26). Two of these two were evacuations without fire, two involved minor external fires, five involved serious external fires that penetrated the aircraft cabin and one involved an internal cabin fire.

5.4.2.2 Available data concerning aisle swapping

The AASK database was then queried for passenger accounts that described some form of aisle swapping. This resulted in a few passenger accounts, although, most of these did not concern aisle swapping to optimise evacuation speed, but were accidentally generated via querying the strings “crossed” and “seating” within the database. The majority of other accounts were from shallow ditching scenarios without fire. These behaviours are considered a feature of the scenario involving evacuations from shallow water with little urgency. As such these accounts have been excluded from this study.

Only one account of aisle swapping of the type witnessed in 90-second certification trials is contained within AASK V3.0 (see Table 27).

Table 27: Accidents that contain passenger accounts contained within AASK V3.0

#	Accident Location	Date	Fuselage Condition (intact / ruptured)	Cabin Smoke (light / severe)	Fire description (minor/major/ internal/external)
9	DALLAS/FORT WORTH INT A/P TEXAS	14 April 1993	Intact	Light	Minor external

5.4.2.3 Available data concerning seat climbing

Turning to seat climbing behaviour, interrogating AASK V3.0 revealed 13 accidents in which passengers had described climbing over seats. However, in some cases the aircraft sustained substantial impact damage and passenger seats were spread over a large area and the cabin was severely disrupted. For example, two accidents were actually referring to instances of passengers extricating themselves from warped and wrecked seating. These instances do not represent an optimisation of an escape route but the only way out of a destroyed cabin. For this reason, these two cases were excluded from further analysis.

A further case involved evacuation without fire following an overrun of the runway and with the cabin containing water. In these types of accidents passengers and crew are reluctant to evacuate at all yet alone optimise their route to the exit. As such this represents a scenario that is beyond the scope of this work. These cases were also discarded from this analysis. This left a final dataset of 10 accidents. Five of these involved fuselage burn through resulting from substantial post-crash fires. Two contained no-fires at all and three were evacuations that involved minor external fires (see Table 28).

Table 28: Summary of the accidents in AASK in which one or more passengers described seat climbing

#	Accident Location	Date	Fuselage Condition (intact / ruptured)	Cabin Smoke (light / severe)	Fire description (minor/major/ internal/external)	Number of accounts
1	CHARLOTTE DOUGLAS INT A/P, NC	25 October 1986	Intact	None	None	1
2	BRAINERD A/P, MINNESOTA	09 January 1983	Intact	None	None	1
3	JOHN F. KENNEDY INT A/P	02 April 1995	Intact	None	Minor external	1
4	DALLAS/FORT WORTH INT A/P TEXAS	14 April 1993	Intact	Light	Minor external	1
5	MANCHESTER A/P ENGLAND	08 March 1998	Intact	None	Minor external	1
6	MANCHESTER A/P ENGLAND	22 August 1985	Intact	Severe	Major Burn-through	16
7	DALLAS/FORT WORTH INT A/P TEXAS	31 August 1988	Ruptured	Severe	Major Burn-through	5
8	DETROIT METRO A/P MICHIGAN	03 December 1990	Ruptured	Severe	Major Burn-through	1
9	LOS ANGELES INT A/P	01 February 1991	Intact	Severe	Major Burn-through	9
10	JOHN F. KENNEDY INT A/P	30 July 1992	Intact	Light	Major Burn-through	1

5.4.3 Method

The accidents have been categorised according to the following categories of fire severity of fire and scenario type, non-fire scenarios, external fire scenarios, burn through fire scenarios and internal fire scenarios.

In this analysis each accident category is discussed in ascending order of fire severity. In this manner the accidents without fire will first be discussed, followed by those accidents involving minor fires and finally those that involved a serious fire. Where available accounts from both passengers and cabin crew are presented. Where appropriate general conclusions are presented with respect to developing a model to simulate the behaviours.

Table 29: Summary of accidents and their relevance according to their type

	Accident Location	Date	Contains relevant accounts to behaviour		
			Redirection / exit choice	Aisle swapping	Seat jumping
Non-fire	BRAINERD A/P, MINNESOTA	09 January 1983	No	No	Yes
	LaGUARDIA A/P NY	02 March 1994	Yes	No	No
	CHARLOTTE DOUGLAS INT A/P, NC	25 October 1986	Yes	No	Yes
External fire	DALLAS/FORT WORTH INT A/P TEXAS	14 April 1993	Yes	Yes	Yes
	MANCHESTER A/P ENGLAND	08 March 1998	Yes	No	Yes
	JOHN F. KENNEDY INT A/P	02 April 1995	No	No	Yes
Burn-through fires	LOS ANGELES INT A/P	01 February 1991	Yes	No	Yes
	JOHN F. KENNEDY INT A/P	30 July 1992	Yes	No	Yes
	DETROIT METRO A/P, MICHIGAN	03 December 1990	Yes	No	Yes
	MANCHESTER A/P ENGLAND	22 August 1985	Yes	No	Yes
	DALLAS/FORT WORTH INT A/P TEXAS	31 August 1988	Yes	No	Yes
Internal fire	GREATER CINCINNATI INT A/P, KENTUCKY	02 June 1983	Yes	No	No

In total 12 accidents are investigated in detail. Of these 10 accidents contain relevant accounts to crew redirection/exit choice, 1 accident contains an account of passenger aisle swapping and 10 accidents contain descriptions of passenger seat climbing (see Table 29).

Before beginning the analysis, it is important to stress that the data contained within the reports should not be assumed to describe every event that took place during the evacuation. Some accounts provide more detail than others. Furthermore, some passengers may consider a possibly important feature of their evacuation too minor to describe. As such the data should be taken as an indication of the some of the qualitative features of the evacuations. Finally whilst useful, this data should be viewed with caution as reports differ in terms of the quantity of data that is available. For example, greater attention is given to evacuation issues in investigations of burn through accidents than non-burn through accident without fatalities. It could therefore be expected for more accounts to originate from the larger and more detailed studies, i.e. those involving fire and loss of life.

5.4.4 Non-fire evacuations

The first 3 emergency evacuations that are investigated did not involve fires. No instances of aisle swapping were present in any of these accidents, however accounts relating to redirection and seat climbing behaviour were present (see Table 30).

Table 30: Non-fire accidents and behaviours contained within accounts

#	Accident Location	Date	Contains relevant accounts to behaviour		
			Redirection / exit choice	Aisle swapping	Seat jumping
1	BRAINERD A/P, MINNESOTA	09 January 1983	No	No	Yes
2	LaGUARDIA A/P NY	02 March 1994	Yes	No	No
3	CHARLOTTE DOUGLAS INT A/P, NC	25 October 1986	Yes	No	Yes

5.4.4.1 Brainerd Airport, 1983

On the 9th of January, 1983 the propeller of a Convair 580 hit a snow bank, separated and penetrated the aircraft whilst landing. The aircraft swerved to a halt and evacuation ensued.

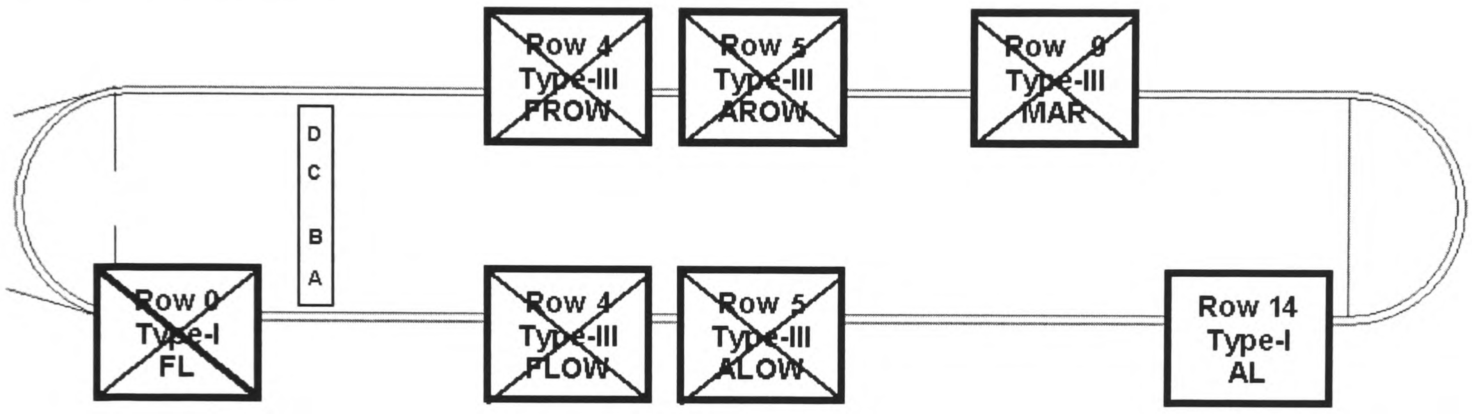


Figure 35: Cabin configuration and exit availability of the Convair 580 at Brainerd in 1983 (crossed out exits were unavailable)

The configuration and exit availability during the evacuation is shown in Figure 35. The aircraft contained seven exits two of which where in pairs. Of these only the AL exit was used during the evacuation. Seating was configured four abreast throughout the aircraft.

Of the 30 passengers onboard, 28 escaped injury. Of the remaining two passengers, one was killed and one injured by the penetration of the fuselage by the propeller blade. The single cabin crewmember survived without injury. General evacuation conditions within the aircraft were relatively good. The only impediment to evacuation was some minor damage to the cabin at the point where the propeller blade entered the cabin.

In total there were 22 passenger accounts contained within AASK V3.0 for this accident. 19 of these were obtained from reported passenger transcripts and three were inferred from the accounts of others.

Events relating to seat climbing

Or umping was contained within this accident. It wa ıe stated that she unfastened her seat belt and climbed over a seat. She stated that she climbed the seat in order to avoid some debris in the aisle. She further stated that some seat backs were "knocked down" before the aircraft came to a halt.

Main findings

No redirection events were reported and aisle swapping was not possible for this aircraft type. However, the evacuation yielded two passenger accounts of seat climbing behaviour, one of which was discounted from this study. The remaining account was an instance of a passenger circumventing an obstruction rather than congestion. Both accounts are not examples of passenger optimising their routes to exits but more finding the only available route to the exit.

5.4.4.2 LaGuardia A/P, 1994

On the 2nd of March, 1994, an MD-82 rejected take-off and overran the runway at LaGuardia Airport New York. The aircraft came to rest with its nose resting on a dyke of tidal mud flats.

All of the 110 passengers and 4 cabin crewmembers escaped alive. However, 29 passengers sustained minor injuries. There were three pairs of exits fitted to this aircraft and two singular exits - a lone port side service door and tail cone exit at the rear of the aircraft. From front to rear the exit pairs were of, Type-I, Type-III and Type-III. Only the right side of the Type-III over wing exits were used during the evacuation and both of the forward exit pair. Seating was arranged 2-2 abreast forward of row 5 and 2-3 thereafter. The aircraft configuration and exit availability can be seen in Figure 36.

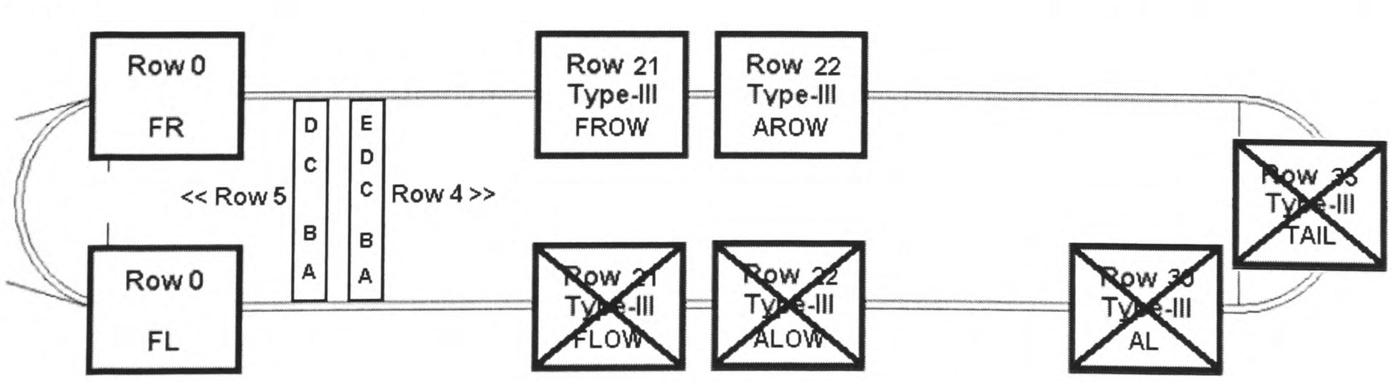


Figure 36: Cabin configuration and exit availability of the MD-82 at La Guardia in 1994 (crossed out exits were unavailable)

Physical cabin conditions during this evacuation were probably better than in 90-second certification trials. For example, there was little reported debris in aisles, cabin lighting was reported as excellent and the aircraft was not carrying its full passenger payload.

Within AASK there are only 14 passenger entries for this accident. These were all based on data taken extracted from air accident reports. In total there were four entries from cabin crew contained within AASK V3 for this accident. They are all based on full transcripts of their personal testimonies.

Events related to crew redirection

a) Passenger accounts

None of the passengers described having to change their direction during their evacuation. However, some passengers described hearing the commands of cabin crewmembers. The first, a female passenger sat in 12D described hearing the commands of cabin crewmembers during the evacuation. She heard someone say *"'come forward towards the light' not the over wing exits"*. Another two females, one sat in 15A the other in sat 12F both reported hearing the cabin crewmembers calling "come forward".

However, this is counter balanced by the accounts of other passengers. One seated in 21A, stated that *"no-one was there helping us. The flight attendants said nothing. We never had any help or announcements"*. Another passenger seated in the rear portion of the aircraft (26F) stated that *"[passengers] took over their own evacuation and the flight attendants did not direct [passengers]"*. These two accounts seem to contradict the statements presented earlier. Examination of the passengers seating location indicates that the negative accounts generally come from passengers seated in the aft portion of the cabin. From this it appears that the aft cabin crewmember was not assertive during the evacuation, however the forward crewmember was. This appears to confirm the notion that crew should be assigned individual levels of assertiveness with the prototype model.

b) Crew accounts

Whilst passenger accounts of redirection are scarce within this accident, cabin crewmember accounts do make reference to some redirection that occurred. The details of these accounts are presented below.

Firstly, the 55 year old female cabin crewmember stationed at the FR exit stated that she moved through the cabin in order to redirect approximately 5 or 6 passengers from the mid-portion of the cabin towards the front exits. She stated that the passengers complied with her wishes. As she stated in her account,

"when the main flow stopped, the FL attendant and I were at the front, and we saw people standing in coach, and we hollered at them 'come forward' which quite a few did."

By implication the FL cabin crew must also have been involved in cabin management procedures during this evacuation, although she did not state this in her account.

Another redirection event occurred at the rear of the aircraft. This was instigated by the 57 year female cabin crewmember stationed at the AL exit. She decided that the AL escape slide had deployed at too steep an angle for safe use. Consequently, she decided to redirect passengers forwards to other exits. As she stated in her account,

"... [passengers] came to the back to go out the galley door, I told them we were not evacuating out there, it was too steep, and to go over the wing or all the way to the front ... I told them the exit is blocked, go to the wing".

This cabin crewmember also stated that passengers responded to her commands. Recall that the passengers stated that they were not assisted during their evacuation.

These two redirection events demonstrate that redirection occurred in this emergency evacuation. Furthermore, it is apparent that it occurred for two different reasons.

In the first instance passengers were directed forwards from the mid portion of the cabin as the forward exits had exhausted their supply. In this instance the cabin crewmembers made a judgement similar to that witnessed in 90-second certification trials. They decided it would be beneficial for evacuation as a whole if some of the passengers in the aft of the cabin utilised the idle exit capacity at the front of the aircraft. Recall that cabin conditions during this evacuation were not unlike the 90-second certification trial scenario. In fact they were probably marginally better. The passengers generally rated the performance of the crew that performed the redirection as being assertive and stated that they obeyed their commands. Recall that the crew try to generate the fastest evacuation time for the whole aircraft population. Dependant upon the passenger flows and configuration of the aircraft, the implication of a redirection decision on the passengers that are redirected can be that they incur a longer personal evacuation time. It is not known in this accident if this was the case.

The second form of redirection that occurred was redirection away from an inactive/unusable exit. This type of behaviour already exists within airEXODUS and does not require a new model. It is however relevant to note that these passengers didn't state that they redirected because the cabin crewmember had instructed them to but made their own decisions and that in these instances the cabin crewmembers were not assertive in their actions.

Main findings

This aircraft type was not appropriate for aisle swapping behaviour and no passenger seat climbing behaviour was reported. However with respect to crew redirection, this accident has demonstrated that cabin crewmembers were able to redirect passenger in the way witnessed in 90-second certification trials. Furthermore, this accident showed that when the crew issued their instructions in an assertive manner that the passengers obeyed their commands. However, those passengers that were not assertively instructed followed their own evacuation plans. This is different to behaviour in 90-second certification trials in which passengers are totally compliant to crew instructions.

5.4.4.3 Charlotte Douglas, 1986

On the 25th of October, 1986, a B737-222 over ran the runway at Charlotte Douglas International Airport, North Carolina, impacted with the ILS localiser antenna, a concrete culvert and chain link fencing coming to rest pitched slightly upwards on a railway embankment.

Of the 114 passengers and three cabin crewmembers onboard there were 31 injuries to passengers and one injured cabin crewmember. The aircraft contained 3 pairs of exits. From front to rear they were of, Type-I, Type-III and Type-I. All of the exits with the exception of the AR were used during the evacuation. Seating was configured in the 3-3 arrangement, with the exception of the Type-III exit row (row 9) where the out board seat was removed.

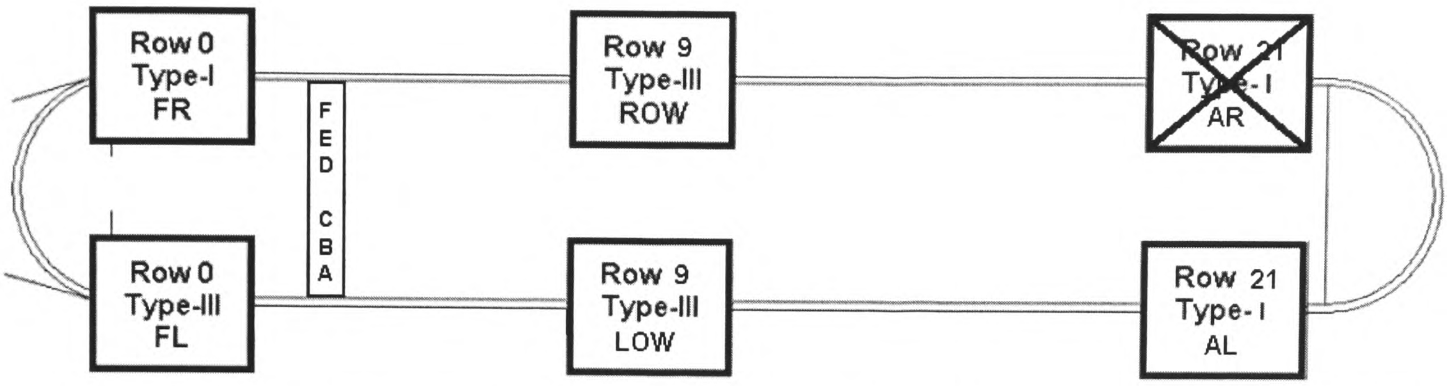


Table 31: Cabin configuration and exit availability of the B737-222 at Charlotte Douglas in 1986 (crossed out exit was unavailable)

Conditions within the cabin were broadly equivalent to those in 90-second certification trials. There was some luggage and debris in the aisles and visibility was good. In addition more than 50% of the available exits were used during the evacuation.

Contained within AASK V3.0 are 114 passenger entries. Of these 111 are based on transcripts report in air accident reports and three are inferred from the accounts of others. Three cabin crewmember entries are also available. These were based on full transcripts of their personal accounts.

Events related to crew redirection

a) Passenger accounts

There are only a few accounts in which passengers describe changing direction within the AASK database for this accident. The first was from a male seated in 12B, and was to rescue/warn two intoxicated passengers who had not realised that the aircraft had experienced an accident. In addition to this there were two accounts in which passengers described hearing cabin crewmember instructions.

The second was from a 43-year-old female passenger seated in 13A. She reported hearing the cabin crew calling "come forward". This passenger exited via the LOW exit located at seat row 10. Another account was from a male passenger seated in 12B. He stated that he heard cabin crew calling passengers forward. Again this passenger exited via the LOW exit.

b) Crew accounts

Two accounts from cabin crewmembers described attempting to redirect passengers forward through the cabin. The first was from the 26-year-old male cabin crewmember stationed at the FL exit. He stated that he called to the centre of the cabin for passengers to come forward. He went on to explain why, stating that he took this action because he observed that passengers were *"bunched up"* at the over wing exits. This version of events was corroborated by the 39-year-old female senior cabin crewmember stationed at the FR, who stated that passengers were *"piled up around the window exits"*. Both expressed difficulty in motivating passengers to move forward within the cabin. The FL cabin crewmember stated that the passengers hesitated, whilst the FR cabin crewmember stated that the passengers disobeyed her instructions. Both of the crew described environmental conditions within the aircraft cabin as *"fine"* and the evacuation as orderly. Furthermore all of the cabin crewmembers stated that they could be seen and heard throughout the evacuation.

Main findings

This aircraft type was not appropriate for aisle swapping behaviour and no seat climbing behaviour was reported. However, with respect to crew redirection procedures it is apparent from this accident that there were attempts at redirection within the cabin. Again, in this instance it was initiated by the cabin crewmember and was aimed at expediting the evacuation of the aircraft as a whole. The cabin crewmembers explicitly stated that reducing congestion was the reason for attempting redirection. In this respect, the crewmembers acted in a way that was similar to 90-second certification trials.

However, unlike certification trials the passengers were not totally subservient to their commands. In this accident, some passengers hesitated and disobeyed instructions. Unfortunately, they did not explain their reasons for doing so, however it seems likely that they judged that the requested action would likely increase their personal evacuation time and so decided against the requested action.

5.4.5 External fires

The following 3 accidents involved external fires, which did not penetrate the aircraft fuselage during the evacuation and contain references to redirection/exit choice, aisle swapping and seat jumping.

Table 32: External-fire accidents and behaviours contained within accounts

Accident Location	Date	Contains relevant accounts to behaviour		
		Redirection / exit choice	Aisle swapping	Seat jumping
DALLAS/FORT WORTH INT A/P TEXAS	14 April 1993	Yes	Yes	Yes
MANCHESTER A/P ENGLAND	08 March 1998	Yes	No	Yes
JOHN F. KENNEDY INT A/P	02 April 1995	No	No	Yes

5.4.5.1 Dallas-Fort Worth, 1993

On 14th of April 1993, a DC-10-30 left the runway at Dallas-Fort Worth, Texas in poor weather conditions shortly after landing. The forward landing gear collapsed during the accident and the aircraft came to rest nose down and listing to port at the side of the runway.

The DC-10 had four pairs of exits, the first being Type-I, followed by Type-A, Type-III and Type-I. The evacuation was somewhat problematic. Since there was a potential fire threat on the left wing the cabin crewmembers initially attempted to utilise all of the starboard exits (FR, MFR, ROW, AR) and the two forward exits (FL and MFL). However, as the orientation of the aircraft was forward and to port, the escape slides on the starboard side of the cabin deployed at extremely steep angles. Approximately midway through the evacuation the cabin crewmember at the ROW exit judged that its use was too dangerous to be continued. In addition the AR escape slide was flipped by the wind thus reducing its evacuation capability to one lane. Seating was in the 2-5-2 configuration, except for the first six rows which were in the 2-2-2 configuration. The configuration and exit availability is shown in Figure 37.

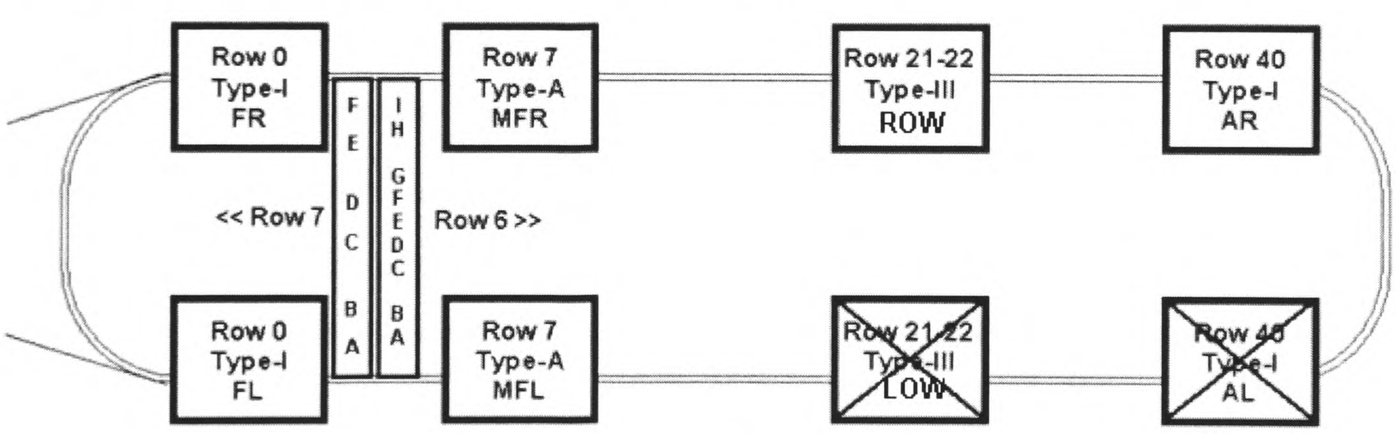


Figure 37: Cabin configuration and exit availability of the DC-10 at Dallas Fort-Worth in 1993 (crossed out exits were unavailable)

The entire passenger and crew complement of 189 passengers and 10 cabin crewmembers all evacuated the aircraft. Of these 37 passengers and 2 crewmembers were injured. During the evacuation cabin crewmembers and passengers saw a minor fire erupt on the left wing of the aircraft.

Physical conditions within the cabin were marginally worse than a standard 90-second certification trial; some passengers described luggage and debris within the cabin. Furthermore, the aircraft attitude was nose down and listing to port. Many passengers in the middle and aft portion of the aircraft saw smoke and flames outside of the cabin. Finally, the emergency lighting system failed. Evacuees described the cabin as *"blacker than black"* (MFR) and that they *"could not see because it was real dark"* (FL).

Contained within AASK are 111 passenger entries for this accident. Of these 64 are based on full transcripts of passenger testimonies, 7 are based on reported testimonies in air accident reports and 40 were inferred from the descriptions of others. In total 7 crew member entries are available. Six are based on testimony transcripts and one is based on a summary style of transcript.

Events related to crew redirection

From the accounts within AASK it appears that redirection mainly occurred in two locations, either from the ROW exit or from the AR exit. The following descriptions of redirection events were provided within passenger testimonies.

a) Passenger accounts

The first passenger account found was from a 61-year-old male passenger seated in 13H, who reported that a cabin crewmember had instructed him to redirect from the MFR exit to the MFL exit. He followed the instructions and finally evacuated via the MFL exit. No more information was contained on this passenger within AASK.

Two passengers, a husband and wife, aged 68 and 58 respectively were seated in 19A and 19B. Both initially redirected from their nearest exit; the LOW to the ROW exit. The 58-year-old wife exited via the ROW onto the starboard wing. Once on the wing, the cabin crewmember instructed her to re-enter the cabin and to exit elsewhere. Instead she disobeyed and jumped onto the near vertical ROW slide. In justification of her action she stated that she thought that the aircraft was about to explode. Her husband was forced to redirect from the ROW as he was pushed back by a *"crowd"* of people re-entering the cabin via the ROW exit. Both stated that they heard cabin crewmember commands during the evacuation.

A 62 year old male passenger who was seated in 17H attempted to evacuate via the ROW exit. Having evacuated onto the wing, a cabin crewmember told him that the escape slide was not useable so he redirected to the MFR exit. Two more passengers from the same seating row, a husband and wife pairing seated in 17A and 17B, also initially attempted to evacuate via the ROW exit. However, the husband stated that he heard someone say that the ROW exit was unavailable. Both redirected from the ROW exit to the MFR exit.

Another husband and wife pair, seated in 23A and 23B, redirected from the ROW exit to the MFR exit. The husband stated that he decided to redirect from the ROW, as he observed that the orientation of the off wing escape slide was too steep. Furthermore, the husband stated that he did not hear any instructions from cabin crewmembers during the evacuation.

A husband and wife seated in 21J and 21H who had evacuated onto the starboard wing were redirected away from the ROW exit back into the cabin. The husband stated that both he and his wife were redirected by the cabin crewmember.

Another instance of redirection was from a 31-year-old female seated in row 25. She stated that she waited 15 seconds in a queue at the ROW exit before hearing someone say that the slide was unavailable. She also redirected to the AR exit.

Another wife and husband pairing, comprising of a 72 year old female and a 77 year old male were seated in 26J and 26H respectively. Both initially tried to evacuate via the ROW exit. However, they were both redirected by the cabin crewmember to the aft exit. At the aft exit they encountered a stationary queue and were redirected back to the ROW exit. They finally evacuated via the ROW exit. They did not state whether they heard cabin crewmember instructions during their evacuation.

A female passenger seated in 26F (not related to the previous passengers), followed a similar evacuation route. However her rationale for redirecting was somewhat different. She stated that frightened passengers and the sight of fire and smoke at the aft exit as her reason for choosing to return to the ROW exit.

A 43 year old male seated in 27G stated that he and his family, consisting of his wife and two children, originally attempted to evacuate via the ROW exit. At the ROW exit he was instructed by a cabin crewmember to evacuate via the aft exit. He and his family complied with the command and redirected. However, upon reaching the aft exit the aft cabin crewmember instructed them to use the ROW exit. He stated that this process was repeated many times. Eventually they exited via the ROW exit. The passenger commented that they *"were among the last to leave"*.

Another husband and wife pairing, consisting of a 68 year old male and a 63 year old female seated in 29H and 29J, also described redirection events. They originally intended to evacuate via the AR exit. They stated that they formed this decision as they saw that it was less crowded. However, upon reaching the AR exit they were redirected by the cabin crewmember to use the ROW exit. They finally evacuated using the ROW exit.

A 25 year old male seated in 30C also stated that he initially intended to evacuate via the AR, however he redirected to the ROW exit. Whilst he did not state that he took the action as a result of cabin crewmember instructions, he did state that he heard the commands of the cabin crewmembers at various points during the evacuation.

A dead heading (non-revenue) male cabin crewmember who was a passenger seated in 32D also described being redirected. He stated that he also initially intended to evacuate via the AR exit. However, he stated that he saw that the ROW exit was vacant and so redirected himself and others towards the ROW exit.

In another instance, a 47-year-old female passenger seated in 33H stated that she also initially attempted to evacuate via the AR exit with her family, consisting of a husband and two children. Her husband and one child successfully evacuated via the AR exit. However, shortly afterwards the escape slide flipped over and the cabin crewmember stationed at the exit began to redirect some passengers away from the exit. She stated that she and her son followed the instructions of the cabin crewmember and evacuated via the ROW exit.

Finally, a male passenger who did not recall his seat number also redirected from the AR exit to the ROW exit. He did not supply any more details of his evacuation.

b) Crew accounts

A s ı the cabin crewmember accounts within AASK.

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The first account was from the female cabin manager. During this evacuation she had a free role and attempted to manage the flow of passengers within the cabin. She did not express any difficulties in redirecting passengers. As she stated in her testimony:

"...there seemed to be a [ROW] tie up. I screamed to come this way and started to run down the aisle. I think [an attendant] saw and was sending people my way..."

The male cabin crewmember stationed at the AR exit stated that he ceased evacuating passengers via the AR exit when the slide flipped over. He also stated that he subsequently continued to evacuate passengers via the exit using the single operable lane of his escape slide. On the basis of reduced exit capacity he redirected approximately 15-20 passengers from the AR exit to the ROW exit. This is an important event as it demonstrates a crew successfully redirecting passengers away from an active exit.

The cabin crewmember that was responsible for the right over wing exit spent much of the evacuation on the wing. She stated that some elderly passengers refused to use the off wing escape slide as the angle was so steep. Therefore, she decided to cease evacuation via her assigned exit (ROW) and to redirect passengers forward.

Finally a female cabin crewmember stationed at the FL exit stated that she diverted passengers away from the unusable FL exit towards the useable FR exit.

Events related to aisle swapping

Only one account of passenger aisle swapping was present in this accident. This was from a 31-year-old female seated in 25A. This passenger moved around the aircraft a considerable amount. She initially moved towards her nearest exit (AR) but found it to be unusable. Consequently, she attempted to use the AL but the cabin crewmember directed her away from this exit as she considered it unsafe for use at that time. She began to move up the cabin in the left aisle however whilst doing so the crewmember at the AR exit decided that the AR exit was again useable and began calling passengers back aft wards. The recently redirected passenger complied with the instruction however noticing that the left aisle was empty she switched aisles to ex

Events relating to seat climbing

Only one passenger account of 'seat climbing' is contained within the AASK database for this accident. The account was described previously under aisle swapping It is likely that the seat jump that she described occurred during the switching of aisles.

Main findings

This accident contained one report of seat climbing and aisle swapping behaviour which were found to be the same event. In the example the passenger swapped into an empty adjacent passenger aisle. This account demonstrates a similar event to those seen in 90-second certification trials in which the passenger swaps into an empty aisle.

Numerous accounts concerning crew redirection were available within AASK. From these, it is apparent from passenger and crew testimonies that redirection occurs. These testimonies suggest that the majority of passengers did as instructed. However, there was an instance of somebody disobeying cabin crew commands. Some passengers claimed to redirect themselves on the basis of the congestion within the cabin. These accounts further support the inclusion of varied levels of passenger subservience and a method for passengers to decide to redirect themselves in any prototype models of this behaviour.

In one instance a cabin crewmember decided to redirect some passengers due to a reduction in exit capacity – the escape slide flipping halved the AR exit capacity. Noticing this, the cabin crewmember sought to better balance the passengers that required evacuating. As it transpired she made a poor decision, as she redirected some passengers away from a useable exit and towards an unusable exit. This event is significant as the passengers followed her instructions – despite them being ill advised with hindsight.

However, this event suggests that the prototype model should take account of dynamic changes in the flow rate capability of exits. In other words the exit flow capability should not be purely static as was the case in the original model, but should adapt if the actual achieved flow conditions are significantly different.

5.4.5.2 Manchester, England, 1998

On the 8th of March 1998 a DC-10 was evacuated following the discovery of a fuel spill at Manchester Airport, England. Whilst the passenger load and injuries associated with this evacuation are not documented within version 3.0 of AASK, it is known that no deaths occurred.

The aircraft contained eight exits. From front to rear they were of Type-I, Type-A, Type-A and Type-A. All eight exits were prepared for evacuation. However, the escape slides of the FR and ALOW exits failed to deploy properly. The evacuation was achieved through the remaining six exits. Lack of information prohibited further definitive knowledge of the cabin configuration for this accident.

Cabin conditions in this accident were much like the 90-second certification trial. However, there was not any debris or luggage within the cabin. In addition the cabin was well illuminated throughout the evacuation and 75% of the total number of exits were used.

In total 126 passenger accounts were available in AASK for this accident. Of these 199 were taken from full passenger testimonies and 7 were inferred from the accounts of others. No accounts from crew members were included within AASK for this accident.

Events related to crew redirection

a) Passenger accounts

Contained within AASK are numerous passenger accounts of redirection, mainly involving redirection away from the exits whose escape slides malfunctioned. Much redirection occurred in the over wing exit area and involved passengers being redirected mainly forwards to other exits. These accounts are presented below.

The first account was from a 55 year old male seated in 18B who initially attempted to use the ALOW exit. He stated that he *"...was told to find another..."* as the *"...chute did not work"*. He finally evacuated via the AROW exit. He explicitly stated that he heard cabin crewmember instructions during the evacuation. Another passenger, a 48 year old male seated in 18A, described a similar chain of events. However, he did not state whether he heard cabin crewmember instructions during the evacuation. His final choice of exit was unknown.

Similarly, a 48 year old female passenger seated in 20D was redirected from the wing back into the cabin to use another exit. She finally evacuated via the FL exit. She also explicitly stated that she heard the instructions of cabin crew during the evacuation. There were 3 other descriptions of redirection from the wing back into the cabin.

A 29-year-old female passenger seated in 34D also redirected away from the ALOW exit. She stated that it *"...did not work properly so we had to cross the plane"*. This passenger finally evacuated via the MFR exit. She did not state whether she had heard the commands of cabin crewmembers or not or whether she was outside of the cabin.

A 62-year-old female seated in 34G redirected from an active exit. However, she stated that overcrowding at her original choice of exit led to her forming the decision to redirect. As she put it, *"our nearest exit was crowded so we ran down empty aisle [sic] to next exit and got out immediately"*. This passenger finally evacuated via the FR exit.

Another instance of redirection was described by a 49-year-old female seated in 36K. She described the event thus:

"we [her spouse was sat in 36H] tried the exit ahead of us but it became very congested because the port side chute had not opened and passengers from that side were using our starboard exit. So my husband and I turned and walked to the rear exit but the stewardess yelled at us in an aggravated tone and ordered us back to the exit we had just tried. By then there were fewer people in line for that exit so we used it."

They finally evacuated via the AROW exit.

Numerous redirection events were localised around the aft exit pair. This resulted from the AL escape slide taking longer to inflate that normal. These accounts now follow.

A 35-year-old male seated in 41K stated that he originally attempting to use the AL exit. However, he was temporally redirected to the AR exit as the escape slide took some time to inflate. He evacuated via his original choice of exit (AL) once the slide had inflated. Two more passengers, a 64-year-old male seated in 44H and a 59-year-old female seated in 44K described similar actions. However, whilst the male from 41K explicitly stated that *"...crew directed passengers to one [the exit] opposite..."* the male from 44H did not. Both passengers finally evacuated via the AL exit.

A 38-year-old male passenger seated in 42K also stated that an aft exit had problems inflating. However, he mistakenly stated that it was the AR exit that inflated slowly not the AL exit. He stated that he was redirected to the left side exit (AL).

b) Crew accounts

Only passenger accounts were available within the AASK database V3.0 for this accident.

Events relating to seat climbing

From this accident only a single passenger stated that she jumped over seating during the evacuation. This passenger was a 25-year-old female originally seated in 34B. She stated that she had to climb over seats in the centre to exit from the right hand side. It could be that the passenger referred to seat climbing when she actually meant re-entered seat rows. This cannot be known for sure.

Main findings

This accident contained no reports of aisle swapping behaviour. However, an account of aisle swapping behaviour was reported, although it is questionable as to whether this account represents the behaviour under investigation. Regardless, the account was of insufficient detail to draw any conclusions.

With respect to crew redirection, this accident provides much qualitative data on the redirection process. It is apparent from these passenger accounts that redirection occurred frequently during this evacuation. The majority of the redirection was away from unavailable exits and was taken under the instruction of the crew. It appears that in this evacuation the passengers obeyed the commands of the crew. Again there is support for attributing crewmembers with unique assertiveness levels.

In addition, an important feature of these accounts is that some passengers described redirecting themselves. They cited congestion at their original exit choice as justification for their decision and would have been attempting to minimise their own personal evacuation time. It was also apparent that some passengers were redirected multiple times.

Also it was apparent from the testimonies of the passengers in this accident that the crew performed well and were able to assert their will on passengers. This was exemplified by the case of the husband and wife from 36K. These passengers made their own decision to redirect due to congestion. However, they were forced to abandon their plan by the assertiveness of the cabin crewmember.

Indeed, passengers from all quarters of the aircraft commented on the effectiveness of the cabin crew during this accident. For example, it was stated from a passenger in 9A that *"the staff on the plane performed an excellent job"*, by a passenger seated in 17K that he *"heard 'clear' instructions"* and a passenger in 41G that *"cabin crew were very clear in their instructions"*.

Again there is strong evidence to support varied levels of communication assertiveness. Furthermore this accident highlighted the fact that in some real accidents passengers may decide to redirect of their own accord. The judgement process of passengers' initiating redirection is slightly different to that of crew. The crew attempt to minimise the evacuation time for the aircraft as a whole whereas passengers attempt to minimise their personal evacuation time. Thus, it seems necessary to develop a model in which passengers judge the merit of various escape routes for themselves. However, its use during non-fire scenarios should be limited as few passengers actually chose to redirect themselves. It is recommended that it be used in non-fire / external fire scenarios when crew have not issued the passengers with instructions. In this way, the instructions of crew may override the plans of passengers.

5.4.5.3 John F. Kennedy, 1995

On the 2nd of April 1995 a pilot of an MD-11 at John F. Kennedy International airport was alerted by the pilot of a nearby aircraft that he could see an engine fire on his aircraft. The captain stopped the aircraft on the taxiway where evacuation was performed.

This aircraft contained four pairs of lower deck Type-A exits. Of these the FR, FL, MFR, LOW, ROW, MFL, MAR and MAL exits are thought to have been used during the evacuation (see Figure 38).

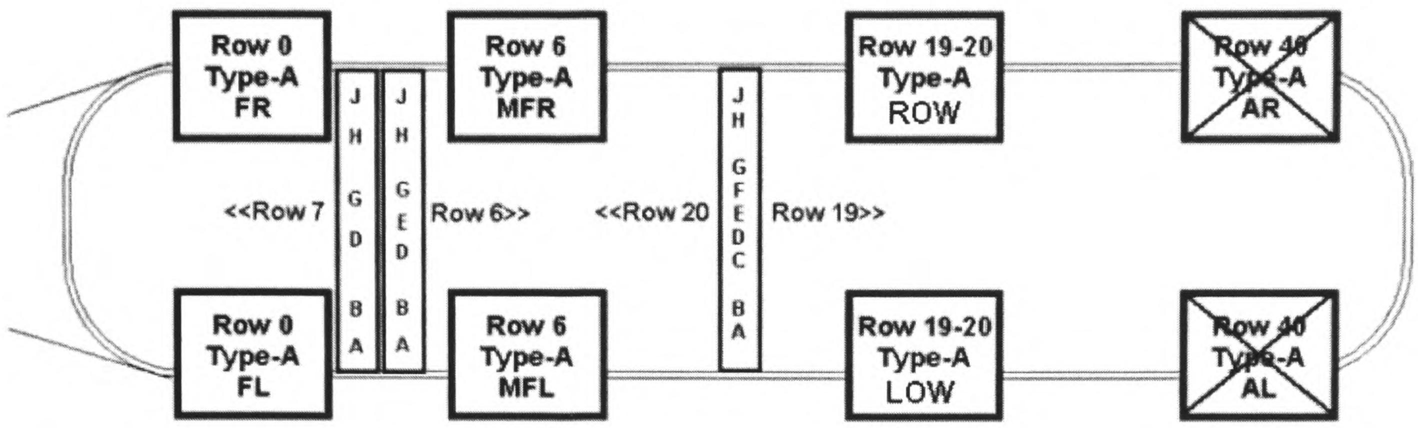


Figure 38: Cabin configuration and exit availability of the MD-11 at John F. Kennedy in 1995 (crossed out exits were unavailable)

Exact information regarding passenger numbers is not provided within AASK V3.0 for this accident. It is thought that 100 passengers were onboard the aircraft. Of these biometric data of the 37 injured passengers were provided to FSEG along with 10 full passenger transcripts. From these transcripts a further two accounts of passengers were inferred, thus providing a total of 12 passenger accounts within AASK V3.0 for this accident.

Whilst the external fire burned through the fuselage and destroyed the aircraft during the period that evacuation occurred conditions during the evacuation were relatively good. Only a few passenger accounts described seeing light smoke during the evacuation. The only obstructions that passengers described during the evacuation were from other passengers. Thus, whilst this accident could be classed as a burn-through scenario conditions were non-severe during the evacuation phase within the aircraft cabin itself.

Events related to seat climbing

The only account of seat climbing from this accident comes from a male passenger seated in 34H. He described his route being blocked with passengers who were searching for belongings. Thus, he decided to climb over 13 rows of seating to reach the LOW exit.

Main findings

This accident demonstrates an instance of passenger seat climbing in an evacuation that did not involve a major fire. Furthermore this account demonstrates a passenger climbing many rows of seating to completely circumvent congestion. No accounts relating to either cabin crew redirection or passenger aisle swapping were reported in this accident.

5.4.6 Cabin burn through fires

The following 5 accidents involved substantial fires that penetrated the cabin fuselage. All of these accidents contain references to crew redirection/exit choice and seat jumping behaviour and none contain reference to aisle swapping behaviour (see Table 33).

Table 33: Burnthrough fire accidents and behaviours contained within accounts

#	Accident Location	Date	Contains relevant accounts to behaviour		
			Redirection / exit choice	Aisle swapping	Seat jumping
1	LOS ANGELES INT A/P	01 February 1991	Yes	No	Yes
2	JOHN F. KENNEDY INT A/P	30 July 1992	Yes	No	Yes
3	DETROIT METRO A/P, MICHIGAN	03 December 1990	Yes	No	Yes
4	MANCHESTER A/P ENGLAND	22 August 1985	Yes	No	Yes
5	DALLAS/FORT WORTH INT A/P TEXAS	31 August 1988	Yes	No	Yes

5.4.6.1 Los Angeles, 1991

On the 1st of February 1991 a Fairchild Metro liner, carrying 20 passengers and one cabin crewmember, crossed an active runway and collided with a departing B737-300 during its takeoff roll. The Fairchild Metro liner jammed underneath the forward fuselage of the B737 and was instantly destroyed killing all of the passengers onboard. Following the impact the B737-300 lost control and crashed into a disused fire station where fire engulfed both aircraft. The fire was severe completely destroying the Metro liner and penetrated the B737 cabin through the floor where the Metro Liner was embedded. Consequently, the fire in the B737 was of greatest intensity where the Metro Liner was jammed, e.g. in-between the forward and over wing exits.

The B737-300 had a pair of forward Type-I exits, a pair of Type-III over wing exits and an aft pair of Type-I exits. The FR, LOW, ROW and AR exits were used during the evacuation. The first two rows of seating were arranged in the 2-2 configuration with the remaining seats arranged in the 3-3 configuration. Cabin crewmembers were stationed at the forward and aft exits. The cabin layout and exit availability can be seen in Figure 39.

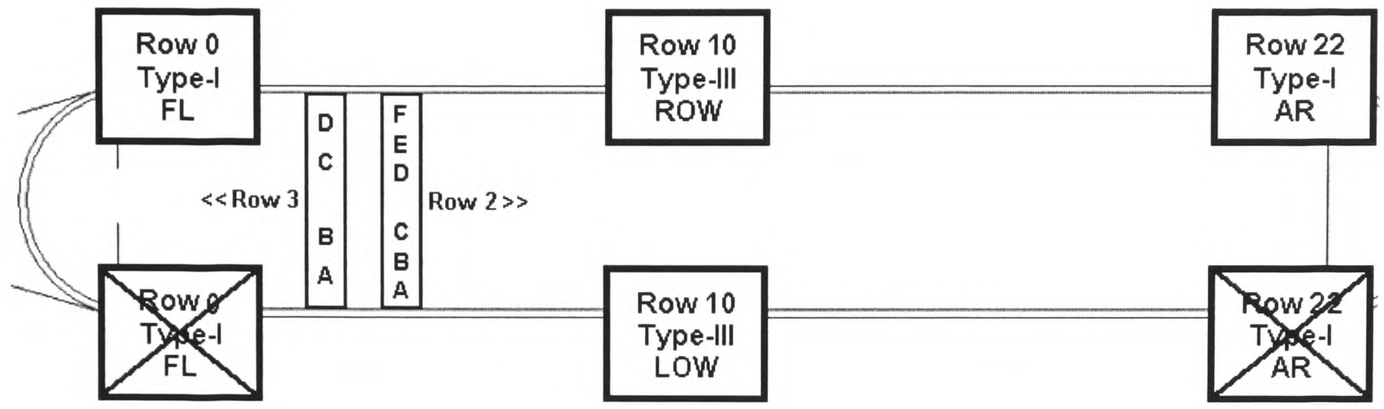


Figure 39: Cabin configuration and exit availability of the B737-300 at Los Angeles in 1991 (crossed out exit was unavailable)

In total 42 passenger accounts from this accident are available within the AASK V3.0. Of these only two are taken from full transcripts and 40 are based on accounts contained with various air accident reports. Data from three full transcripts of cabin crewmember accounts are available within AASK V3.0.

From their descriptions it is apparent that the cabin quickly filled with toxic gas and smoke. Passengers described the effects of the cabin environment as making visibility difficult, some stated the difficulty as being severe, causing them difficulty breathing and/or causing them to hold their breath, some were forced to crawl. One passenger described the effects of the smoke as *"choking"*. The female AL cabin crew stated that they *"could not see anything"* and the 23 year old male cabin crew at the FR exit stated that he had *"a real difficult time breathing"*. In conclusion conditions within the cabin were dire.

One cabin crewmember and 20 passengers of the four and 83 that were onboard the B737 perished, mainly from thermo-toxic exposure. The other three cabin crewmembers and 26 passengers sustained injuries during the evacuation. Only 37 passengers avoided any injuries.

Events related to crew redirection

a) Passenger accounts

In total seven passengers described a redirection event. The first was from a 46 year old male seated in 6A. He initially attempted to evacuate at the rear of the aircraft. He moved past the over wing exits. He stated that he then noticed that there were 15 people ahead of him moving aft. He looked around for alternative options and spotted the left over wing exit, which at this time was still closed. He stated that he *"dove over the seats, hit the latches and dove out the exit"*. He also stated that he did not hear any cabin crewmembers throughout his evacuation.

The second account was from a 53 year old female seated in 13F who originally chose to evacuate via the ROW exit. However, she redirected to the LOW exit as she thought that there were too many people ahead of her using the ROW exit. She also stated that she did not hear the commands of cabin crewmembers during the evacuation.

The third redirection event was described by a 22 year old male passenger seated in 15A. He originally attempted to evacuate using the ROW exit, however stated that he decided to redirect to the AR exit as the aisle to the ROW exit became blocked with passengers. This passenger stated that he heard someone shouting instructions during the evacuation.

The fourth was from a 25 year old female seated in 17B. She originally began to move forwards, presumably towards the over wing exits. However, this passenger stated that "choking smoke" forced her to redirect to the AR exit. She did not comment on whether she heard cabin crewmember instructions.

The fifth was from, a 44 year old male who was seated in 17F. He had originally began to move towards the over wing exits. However, chose to redirect to the AR exit as he stated that there were *"hounds of people in centre aisle"*. He also stated that other passengers followed his lead and redirected to the AR exit. He did not comment on whether he heard the instructions of the cabin crewmembers during the evacuation.

The sixth and seventh did not actually change their direction of travel during the evacuation, however described hearing crew commands during the evacuation. Both of these two passengers were situated within 5 rows of the aft exit. The first, a 49 year old male in 19A stated that *"he [the AR cabin crewmember] kept yelling to come to the back door"*. Another, a 26 year old female passenger seated in 21E stated that the AR crewmember *"shouted to come this way"*. She also stated that she *"had plenty of time to get out"* and that the passengers seemed to be moving forwards."

b) Crew accounts

The accounts of the cabin crewmembers corroborate the accounts of the passengers in this emergency evacuation. The first is from a 26 year old female cabin crewmember originally assigned to the AL exit. She stated that she began to redirect passengers from the AL to the useable AR exit. However, she tried to redirect passenger from the over wing exits towards the aft exits. She stated that this was unsuccessful. Her description of events was that *"They were waiting [in the over wing area]. I screamed at them to come, but it was like they were dumbfounded on that [ow] exit"*. The cabin crewmember also stated that she attempted to move to the over wing exit, presumably so as to physically manhandle them, but was forced to turn back by the environmental conditions within the cabin. As she stated, *"[I] could not see anything" and "[the smoke] was thick and I felt it"*. None of the passengers that evacuated via the over wing exits stated that they heard the commands of the cabin crewmember during the evacuation.

The 26 year old male cabin crewmember that was stationed at the AR exit was preoccupied with expediting the use of the escape slide. As such he stated that he did not see much of the proceedings within the cabin.

Finally, the 23 year old male cabin crewmember stationed at forward right exit where the fire was most intense commented that *"I was having a real difficult time breathing" and was "beaten back by flames"*. He also commented that he could not see or be seen and that *"everybody was quiet"*. Only four passengers evacuated from the forward right exit.

Accounts relating to seat climbing

In total there are 9 passenger accounts describing seat-climbing behaviour all of whom evacuated via the over wing exits. Each account is described in order of seat location below.

The first account was from a 23-year-old female originally seated 4D who described crawling across seats to evacuate via the ROW exit. She did not specify how many seats that she crawled over although she stated that shortening the path to the exit was her reason for taking this action.

Another description came from a 46-year-old male passenger seated in 6A. He described moving towards the ROW exit, but noticing that the LOW exit was not open. Having noticed this, he described jumping over a couple of seats, opening the exit and then evacuating through it. He stated that congestion was his reason for climbing over seating.

Another account was from a 22-year-old male seated in 6E who described climbing over 3 rows of seating in order to reach the ROW exit before diving out of it. From his starting position, jumping over three seats would have taken him directly into the exit row. He stated that the sight of passengers jammed in the aisles was his reason for seat jumping.

The next account was from a 36-year-old male who was seated in 7D. He described climbing over one seat to get to the ROW exit. He stated that shortening his route to the exit was his reason for climbing over the seating. Since there were three rows between his initial seating location and the exit row, he must have entered the aisle only to later climb over seating once he was within a single seat row of the exit.

Another account was from a 29-year-old male seated in 9F who described jumping over the single row of seating that stood between him and the ROW exit. He stated that minimising the distance of his route to the exit was his primary reason for seat jumping. Furthermore, this passenger stated that he started seat jumping almost immediately that the evacuation begun.

Another account was from a 32-year-old female seated in 11C. She described climbing over one row of seating. This would have taken her directly into the over wing exit row. She stated that she had to climb over the seats in order to reach the exit due to other passengers blocking her preferred route.

Another instance was from a 51-year-old male seated in 11D. This passenger stated that he noticed that the back of the seat at 10E could be pushed down to afford access to the exit row. Having noticed this, he pushed the seat back down and climbed into the exit row, where he proceeded to open the exit.

Another passenger, a 26 year old male seated in 15F described having to travel over seats to get to the ROW exit. He stated that shortening his route to the exit was his reason for this behaviour.

Finally, a 37-year-old male seated in 14D also described jumping over seats. His description of this event within AASK V3.0 was short. He only stated his reason for jumping seats, which was to reduce the route to the exit. This passenger also described seeing other passengers "running" over the tops of the seats.

Main findings

No reports of aisle swapping were contained within AASK for this accident. However numerous accounts of redirection were reported. From the passenger accounts of this accident contained within AASK, it appears that those passengers that changed direction did so regardless of cabin crew instructions. Furthermore, most stated that seeking to reduce the number of people in the queue ahead of them as their reason for redirection. In other words they were trying to minimise their own personal evacuation times. This conclusion is even apparent from the accounts of the two passengers that categorically stated that they heard the cabin crewmember calling for passengers to move aft who observed that the majority of passengers were moving forwards.

The cabin crew described their effectiveness as being severely reduced by the cabin conditions. Furthermore, the accounts of the cabin crewmembers indicate that most passengers either did not hear or ignored the commands of the cabin crew. Consequently they made their own evacuation decisions that were, invariably, based on a personal assessment of the quickest available evacuation route. However with hindsight, their decisions may not have actually achieved the fastest evacuation possible. This was highlighted by the fact that the aft exit exhausted its supply of passengers. Those passengers at the periphery of the ROW exit queue may have expedited their evacuation by redirecting to the AR exit. However, they did not. The reason for this is unknown. It may be that they simply did not know that the AR exit was available. Alternatively it may not have been possible to see clearly from the OW areas to the aft of the cabin. If so, they may not have realised that the AR exit had exhausted its supply of passengers. Alternatively, they may have over estimated the flow capability of the ROW exit, thus making it a more attractive option than risking a potentially lengthily navigation through the smoke logged aircraft cabin to the AR exit.

From these accounts it is apparent that a passenger initiated redirection model should take into account the environmental conditions within the cabin and the reduced movement speeds that are associated with it. In addition, the conclusion from the non-fire cases that instructions from crew should override the plans of the passengers is not corroborated in this accident. In this case the passengers either did not hear the commands of the crew or decided that they had a better idea of which route provided the quickest exit or where not prepared to move through the smoky environment.

In addition to crew redirection, numerous accounts were available describing seat climbing behaviour. Of these three were from passengers who were seated in rows immediately adjacent to the exit, one was from a passenger who moved through the aisle until he neared the over wing exit where he jumped the adjacent row. In other accounts, one passenger claimed to climb three seat backs. Unfortunately the remaining passengers did not indicate the number seat rows that were jumped.

The reasons that were cited by the passengers for climbing seats were varied. Six stated that they wanted to take the shortest route to the exit, whilst two described congestion as their reason – the remaining passenger did not specify a reason for their actions. Two of the three passengers that jumped the adjacent row seating to the exits stated congestion and the other shortening the route as their reasons. The passenger that jumped three rows did not give a reason for seat jumping.

Passengers that chose to seat jump in this accident were not as young as those in the Manchester accident. However, most of the ages (22,23,24,26,29,32,37,46,51) were below the mean age of passengers contained within AASK V3.0 for this accident (mean age of 34 years). Gender was split with six males and three females describing seat jumping.

Table 34: Summary of those passengers that described seat climbing within AASK V3.0 from the Los Angeles accident in 1991

Seat	Age	Gender	Reason for seat climbing	Exit used	Number of rows climbed
4D	24	FEMALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	Unknown
6A	46	MALE	AISLE TOO CONGESTED	LEFT OVERWING	Unknown
6E	22	MALE	Unknown	RIGHT OVERWING	3
7D	36	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
9F	29	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
11C	32	FEMALE	ROUTE TO AISLE BLOCKED BY PAX	RIGHT OVERWING	1
11D	51	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
14D	24	FEMALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	Unknown
15F	46	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	Unknown

5.4.6.2 John F. Kennedy, 1992

On the 30th of July, 1992 a L1011 aborted take-off immediately following rotation at John F. Kennedy International Airport, New York. In doing so the captain touched down with some force. The Captain determined that the aircraft would not stop before colliding with a blast fence at the end of the runway. He therefore steered the aircraft to the side of the runway where the evacuation ensued. During touch down the aircraft sustained damage that led to the development of a severe external fire that later penetrated the cabin.

Onboard the aircraft was a full passenger complement of 280 passengers and 9 cabin crewmembers. There were no fatalities, although 10 passengers were injured during the evacuation. None of the cabin crewmembers were injured during the evacuation.

The quantity of passenger accounts contained within the AASK database V3.0 for this evacuation is low (39). Of these, 14 were based on full transcripts of passengers, 20 are based on reported transcripts within air accident reports and five were inferred from the accounts of others. Nine cabin crewmember entries were available within AASK. Of these 7 were based on summary style of testimonies and 2 were inferred from the accounts of others.

The aircraft had four exit pairs. The front two pairs and the aft were of Type-A. The MA exit pair was of Type-I. Whilst six exits were opened passengers evacuated through only three, the FL, FR, and MFR (see Figure 40).

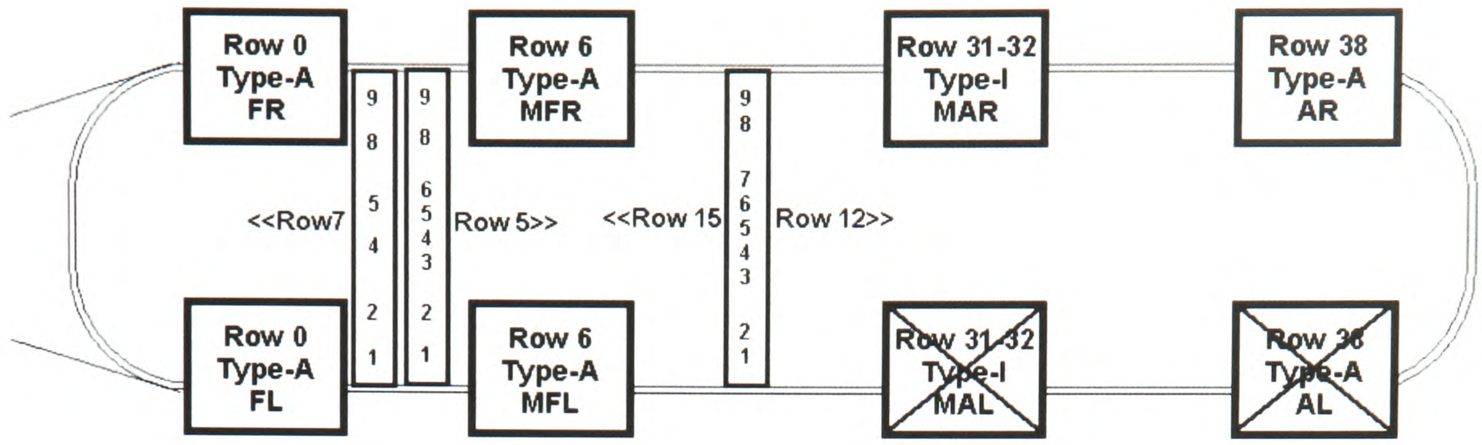


Figure 40: Cabin configuration and exit availability of the L-1011 at John F. Kennedy in 1992 (crossed out exits were unavailable)

Only one passenger, a male seated in 31-1, stated that smoke obscured his vision during his evacuation. This was not corroborated by other passengers and crew. In fact all of the cabin crewmembers stated that they could see and be seen during the evacuation. The physical conditions within the cabin must be considered as close to the 90-second certification trial scenario.

Events related to crew redirection

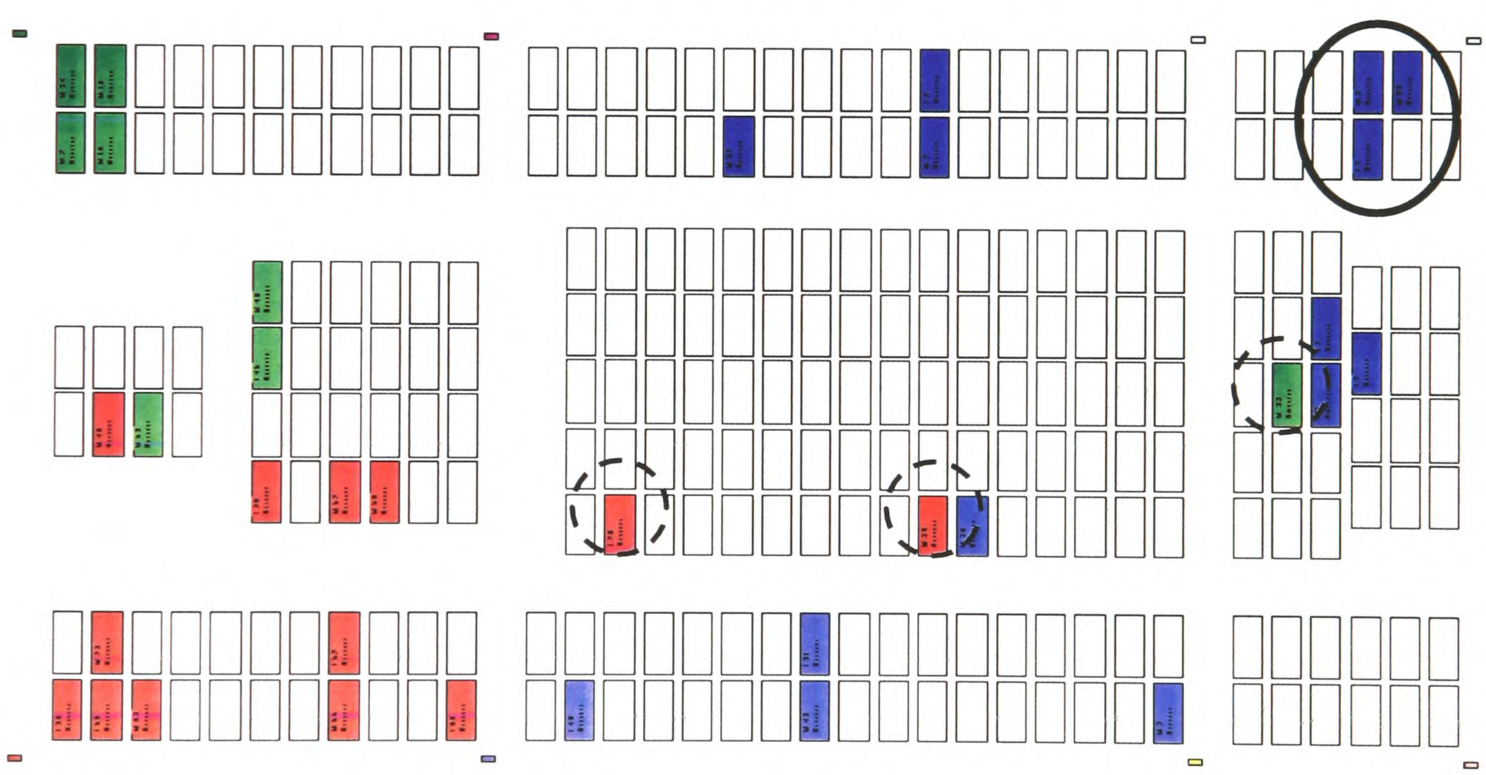


Figure 41: AASK generated seat plan view of exit use during the evacuation of a L-1011 at John F. Kennedy on 30th of July 1992 (circled passengers must have bypassed an exit)

a) Passenger accounts

Only four passenger accounts make reference to redirection events. The first was from a 38 year old male seated in 26-3. This passenger stated that he initially started to move towards the MAL exit, however later he redirected to the forward exits having seen flames at the MAL exit. The second account was from a 53 year old male who was seated in 36-9. He stated that he heard cabin crewmembers saying *"go the other way"*.

He stated that this confused passengers in other parts of the aircraft. The third was from a 63 year old seated in 3-4. This passenger stated that the *"forward flight attendants called pax forward to [the] exit[s]"*. The final reference was from a female seated in 34-5. She described passengers being *"herded"* forward through the cabin.

b) Crew accounts

Cabin crewmember accounts contained within AASK V3.0 on this evacuation are brief. In total nine accounts are available. However, none are taken from full transcripts of their testimony. Seven are taken from a summary presented within an air accident report and two are inferred from the accounts of others. From this data only three accounts make reference to redirection events.

The first is from the 44-year-old female cabin crewmember stationed at the MAL exit. This crewmember reported opening the MAL exit. However, whilst doing so she noticed that smoke and flames entered the cabin. She decided that the exit was not useable and blocked it from passengers. She noticed an *"orange"* glow through the window of the opposite exit in the MA exit pair and decided that this was also unusable. She proceeded to redirect passengers forward. She stated that she had no difficulties in instructing passengers.

The 35-year-old female cabin crewmember stationed at the AL exit followed a similar chain of events. Again she opened her exit and determined from flames and smoke entering the cabin that the exit was unusable. She directed passengers forward to alternative exits. Again, she stated that she thought that she could be seen and heard throughout the evacuation. The 35-year-old cabin crewmember stationed at the AR followed a similar series of events.

From the accounts contained within the AASK database it appears that redirection occurred within this evacuation. From the few passenger accounts that exist it appears that their instructions were heard, although not always understood. Examination of the AASK seat plan viewer revealed that three passengers (dashed circle in Figure 41) bypassed their nearest useable exit, the MFL, and used exits at the front of the aircraft cabin. Thus more instances of redirection occurred than were described. In addition, whilst not mentioned within AASK V3.0 the official NTSB air accident report of this accident states that *"some of them [passengers at the MFL exit] used the FL exit at the* *urging of the duty flight attendant.".* This suggests that the cabin crewmember at the MFR position may have diverted passengers forward towards the under utilised forward exits. Unfortunately the lack of data on this evacuation precludes further conclusions.

Accounts relating to seat climbing

There was only one passenger that stated that they jumped over seating during the evacuation. The account was from the mother of a 35-year-old male who was seated in 35-9. She described her son climbing over some seating in order to switch aisles. He evacuated via the MFL. It is not known whether this description referred to 'squeezing' side-ways through the seating or climbing longitudinally over seat backs.

Main findings

The usefulness of this accident in providing insight for the development prototype redirection sub-models is limited. From the data contained within AASK all that is really apparent is that passengers moved forwards through the aircraft cabin under the instructions of the cabin crew. In addition, there was one reported instance of seat climbing and/or aisle swapping behaviour. The detail of this account was however too small to draw meaningful conclusions.

5.4.6.3 Detroit, 1990

On the 3rd December 1990, a DC-9 taxied onto an active runway and collided with a B727 during its take-off roll. The DC-9 suffered extensive impact damage. A major fire quickly developed which eventually completely destroyed the DC-9 aircraft.

The aircraft contained two pairs of exits and a tail cone exit. Of these only the FR, FL and LOW exits were used during the evacuation. The first two rows of seating were in the 2-2 configuration, with those after in the 2-3 configuration. The seating layout and exit availability can be seen in Figure 42.

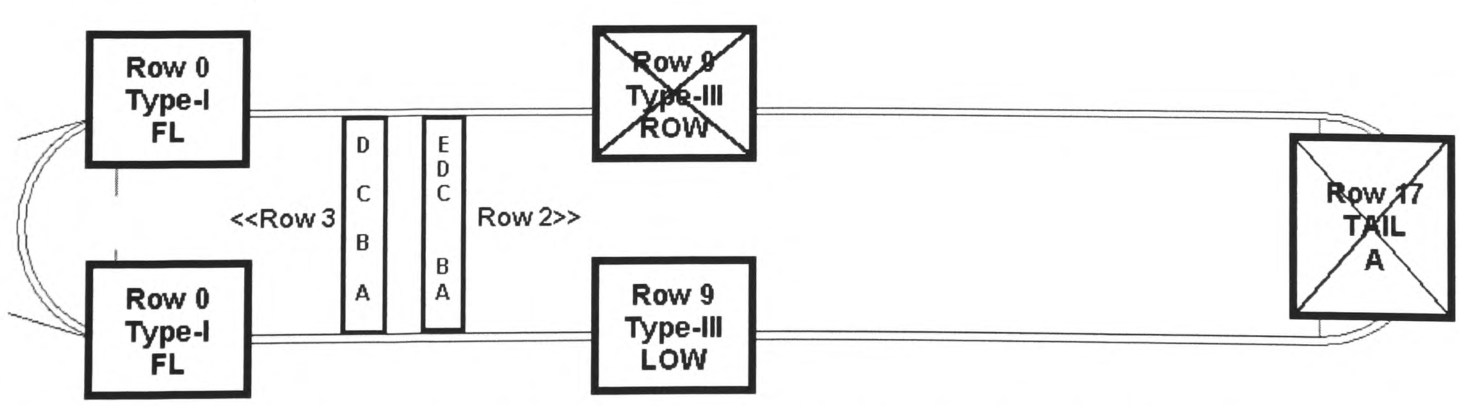


Figure 42: Cabin configuration and exit availability of the DC-9 at Detroit in 1990 (crossed out exits were unavailable)

Onboard the DC-9-20 were 40 passengers and 2 cabin crewmembers. Both of the cabin crewmembers and 31 of the passengers were injured onboard the DC-9. Nine of the passengers that were onboard the DC-9 were killed, mainly from thermo-toxic exposure as the fire penetrated the cabin. The B727 suffered some structural damage but was not subjected to fire. All of the 5 cabin crewmembers and 146 passengers that were onboard the B727 evacuated without injury. This section concentrates purely on the evacuation from the DC-9-20.

Data for only 17 of the 40 surviving passengers are available within the AASK database V3 for this accident. This data was based on reported testimonies taken from air accident reports. Only one crewmember account was available. The cabin crewmember data was taken from a summary style of testimony.

Conditions within the cabin were extremely hazardous. An 82 year old female seated in 18D stated that the cabin contained debris. Furthermore, she stated that expired passengers acted as obstacles to movement in aisles and in negotiating Type-III exit passageways. Another passenger, a male from 9D, stated that visibility was reduced during the evacuation. Passengers stated that they *"saw black smoke at the back"* and another that she saw *"flames in the aft cabin"*. The fire was most intense at the rear of the aircraft. This had the effect of making passengers move forwards, away from the seat of the fire in a very rapid manner. The accounts of passengers indicated that the evacuation was very urgent, exemplified by the account of one passenger who stated that the *"right wall exploded"* during the evacuation.

Events related to crew redirection

a) Passenger accounts

Relevant survivor testimonies from the DC-9-20 concerning redirection events are presented below.

A male seated in 7D stated that the crowd was *"surging"* forward. However, he stated that he thought that there was an exit close by that was not being utilised. He therefore visually searched for it whilst continuing to move forwards. He stated that he spotted a closer exit that was positioned four rows behind him. He shouted for other passengers to open the exit, which they did. He then stated that the crowd surge pushed him through the exit once it had been opened.

Two more passengers stated a similar chain of events. The first, a male seated in 9D stated that he was moving forward when he noticed that the LOW exit had been opened. He subsequently changed direction and evacuated through the nearer LOW exit. The second, a male seated in 10A stated that he too noticed the LOW exit was being used. Having noticed, he backtracked two rows and exited via the LOW exit. This event is also significant as it demonstrates passengers deciding to change their direction of travel during an evacuation.

A male passenger seated in 9D stated that his rapid evacuation benefited from what he thought were poor redirection decisions by others. As he stated *"a great many pax in aisle backtracked, giving him access to the forward exit"*.

b) Crew accounts

There were no comments from the cabin crew relating to redirection within the AASK database for this accident, although in the one account that was available the crewmember commented on the physical cabin conditions, stating that it was dark.

Accounts relating to seat climbing

Only one passenger described seat jumping during this accident. The passenger, a male seated in 11D, stated that he jumped over 2 seats and dove for the LOW exit opening, and landed on the wing. He did not give any more details on his reasons for taken this course of action. The number of rows that he climbed may indicate that he climbed the entire route to the exit.

Main findings

No reports of aisle swapping were reported for this accident. Although one account of seat climbing was present it was of little value when considered in isolation as it merely described an instance of seat climbing behaviour.

Numerous accounts involving redirection were available from this accident. It appears that the redirection in this emergency evacuation was due to a new escape path becoming available. Indeed in this evacuation the majority of passengers opted to use their nearest available exits. This is highlighted by the fact that only 11 passengers are known to have evacuated via the pair of forward exits compared to 6 known to have evacuated through the LOW exit. This is significant as the LOW exit has a third of the evacuation capability of the combined forward exits. In addition, the LOW exit took longer to prepare. In other words many more passengers used the over wing exits than was optimal for the aircraft as a whole.

It appears in this accident that more passengers should have used the forward exits than did. This was highlighted by the account of the passenger in 9D who stated that the mass redirection of others expedited his personal evacuation. Again this demonstrates the unwillingness of passengers to risk movement through a hazardous cabin. The reason for this is again not clear. It maybe that the passengers over estimated the evacuation capability of the nearer Type-III exits, thus perceiving it as a better option than reality. This suggests that passengers do not fully appreciate the flow capability of aircraft exits. They may tend to over-rate the flow capability of some exits, in particular small Type-III exits. This would have the effect of making it more attractive than it should be.

From the accounts within the database it appears that the crew were quite ineffective during the evacuation. Indeed, few passengers stated that they heard any instructions from the cabin crew during the evacuation.

5.4.6.4 Manchester, 1985

On the 22nd of August 1985, a B737-300 suffered an uncontained engine failure during its take-off roll at Manchester Airport, England. The captain aborted take-off and stopped the aircraft at the side of the runway where evacuation ensued. The prevailing wind caused the fire plume from the left engine to be directed onto the aircraft fuselage. The fire penetrated the cabin.

In total there were three exit pairs fitted to this aircraft. From front to rear they were of, Type-I, Type-III and Type-I. Of these only the FL, FR and ROW exits were utilised. There was a large delay of approximately 50 seconds in preparing the ROW exit for use. Seating was arranged in the 3-3 configuration throughout the aircraft. The seating layout and exit availability can be seen in Figure 43.

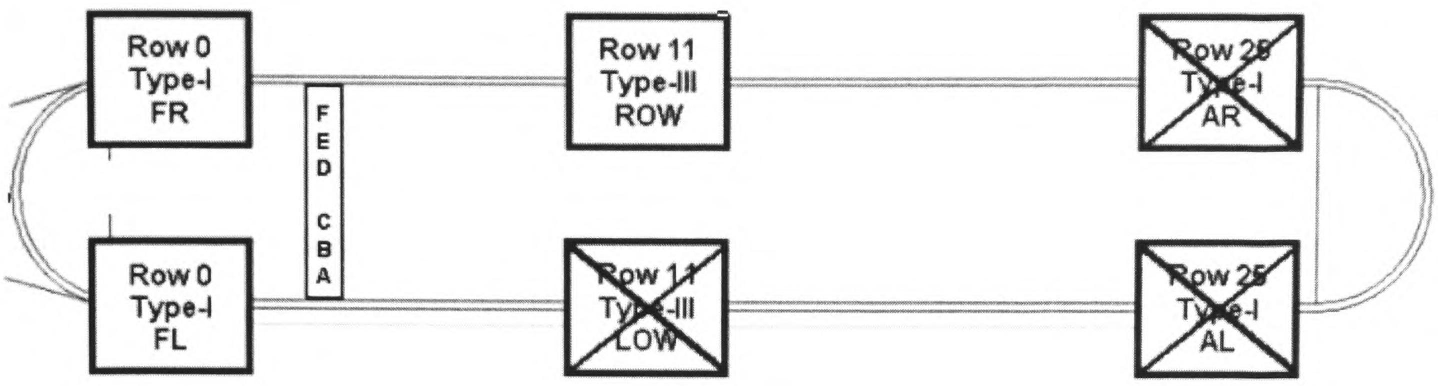


Figure 43: Cabin configuration and exit availability of the B737-236 at Manchester in 1985 (crossed out exits were unavailable)

Conditions within the cabin were extremely hostile to life as toxic gas and smoke was initially sucked through the cabin from the slightly open AR exit and later penetrated through the cabin. Numerous passengers stated that they had difficulty breathing, some were forced to hold their breath and suffered reduced visibility. Graphically a 50 year old male seated in 8D reported using his handkerchief to wipe soot away from his eyes so that he could see better. The cabin manager stated that smoke emanating from the rear of the cabin quickly reached the galley area and became rapidly more dense and acrid. The other cabin crew member stated that the smoke forced her down onto her hands and knees. In addition, the accident investigation found numerous bodies within the aisles and seats adjacent to the over wing exits. Some of these may have acted as obstacles during evacuation. In short, evacuation was perilous.

Two of the four cabin crewmembers and 53 of the 131 passengers onboard the aircraft died from the effects of the fire and toxic gases and a further 15 passengers were injured.

In total 75 passenger entries are contained within AASK V3. These were taken for the full testimonies of passengers. Only 2 cabin crew entries are contained within AASK. Both of these come from summary style testimonies.

Events related to crew redirection

a) Passenger accounts

The first is from an 18 year old female seated in 7E who originally intended to use the ROW exit which was 5 rows to her rear. Having waited in the aisle for some time she decided to redirect to the forward exits. The reason she stated for redirecting was that the aisle was too congested. To circumvent congestion behind her she was forced to climb over seating en route to the front exits. She eventually exited through the FR exit. She described the environment within the cabin as reducing her visibility and causing her to have difficulty breathing. Furthermore, she did not mention whether she heard cabin crewmember instructions or not.

The next account was from a 42 year old male seated in 9C. He also redirected from the ROW exit to the FR exit. He did not explain his rationale in making this decision nor whether he heard the instructions from cabin crew. Neither did he describe the effects of the hostile cabin environment.

Another account was from an 18 year old female seated in 11F, she stated that she attempted to enter the aisle. However, she stated that she could not. Presumably this was because it was packed with other passengers. She followed her boyfriend, who was sat in 11E, and redirected to the forward exits again exiting via climbing over seats. She did not state whether she heard the commands of cabin crewmembers or the effect that the thermo-toxic environment had upon her evacuation. Her boyfriend's testimony was brief and did not describe the evacuation in detail.

A 42 year old passenger in 13D stated that he noticed that the queue in the aisle for the ROW exit was stationary. From his seating location this passenger would have had to move 2 rows forwards to reach the exit. He therefore considered using the LOW exit. However he determined that fire outside the cabin made this choice of action too dangerous. Consequently, he decided to move forwards within the cabin and to head towards the forward exits. He eventually exited through the FL exit. He described the cabin environment as causing him difficulty in breathing. He did not mentioned whether he had heard cabin crewmembers during the evacuation. He did not mention whether he was forced to climb over seating en route to the exit. His family were seated next to him. They also evacuated via the forward exits. Presumably they followed a similar course of actions.

From the AASK seat plan viewer it is apparent that two more passengers, a 24 year old female sat in 14A and her friend a 28 year old male sat in 14B (circled in Figure 44), also bypassed the nearer over wing exit and evacuated using the front exits.

Unfortunately they did not provide a detailed account of their evacuation within their testimonies.

Figure 44: AASK generated seat plan view of exit use during the evacuation of a B737-300 at Manchester England on the 22nd of August 1985 (circle denotes passengers that must have bypassed an exit)

b) Crew accounts

Cabin crew data within AASK V3 is limited for this accident. Hence it was not possible to derive anything meaningful from their accounts.

Accounts relating to seat climbing

In total there are 17 passenger descriptions of seat climbing contained within AASK V3.0 for this accident. They will be discussed in ascending order of their seat location and the exits that they used.

The first account is from a 19-year-old female seated in 3F. This passenger described attempting to climb seats to reach the exit. However, she stated that she was unable to climb over them and fell. She evacuated via the FR exit.

The next account was from a 21-year-old male seated in 6B. He stated that his aisle was moving too slowly and as a consequence he decided to climb over an unspecified number of seats. He finally exited via the FR exit.

Another was from an 18-year-old female seated in 7F who also described climbing over approximately 5 rows of seating. She did not specify her reason. She exited via the FR exit. An 18-year-old female passenger who was sat in the adjacent seat (7E) described waiting for the aisle. However, she stated that it didn't clear and so she decided to travel over the seating instead. She climbed an unspecified number of seats. She also exited via the FR exit. She stated that she followed other passengers (presumably the passenger in 7F) to the exit.

Another account was from a 42-year-old male seated in 9C who described climbing seats on the right hand side of the cabin. This passenger must have entered and subsequently left the aisle in order to climb over the seats on the right hand side of the cabin. He did not specify how many seats he climbed or his reasons for doing so. He exited via the FR exit.

Of those passengers that evacuated via the FR exit, five described climbing seats en route to the FR exit. There was a reasonable spread across gender (4 females and 1 male), but these passengers are mainly youthful, with ages of 18,21,18,18 and 42. Four of the passengers jumped seats on the right hand side of the cabin, two of whom were seated adjacent to each other. The side of the cabin that passengers climbed seating could not be determined for one of the passengers.

Only one passenger stated how may seats he climbed, stating that he climbed approximately 5 rows. Two reasons for jumping seats were stated. They were, that the aisle was moving too slowly and that they followed the actions of another.

The remaining 12 accounts contained within AASK for this accident involved passengers climbing seats en route to the ROW exit. They are each described in turn.

The first was from an 18-year-old female seated in 9D. She described jumping over one row of seating. Another passenger, a 21-year-old male who was seated in the adjacent seat (9E), also described jumping over one row of seating. This passenger stated that he chose his course of action as it offered the shortest route to the exit.

Another account was from an 18-year-old female originally seated in 11F who described attempting to get into aisle but stated that she could not. She described following her boyfriend over seating. It is likely that her boyfriend, a 21-year-old male seated in 11E, may have decided to jump seating for similar reasons and perhaps used the same route.

Another account was from a 14-year-old female seated in 14F who described falling unconscious during the evacuation but recalled climbing over seating during the evacuation.

The next passenger to describe seat climbing was a 20-year-old female seated in 15A who described climbing over several seats before cutting back into the aisle and evacuating via the ROW exit. It should be noted that given her seating location she would have had to climb five seat backs rows to reach the exit. She stated that she took this action as her path out of the seat row and into the aisle was blocked by a male passenger seated in 15C.

A passenger sat in the adjacent seat (15A), and 19 year old female in 15B, also described her path into the aisle being blocked by a male passenger who refused to let her pass. She also described climbing over three seats to reach the ROW exit. Her actions were very similar to the passenger who was sat next to her.

Another account was from a 23-year-old female seated in 15D also described climbing over seats en route to the ROW exit. She did not specify any more information about this event.

The next passenger account within the database of seat climbing was from a 29-year-old female who was originally seated in 18E. She described climbing over seats to head straight out of the ROW exit. Her friend who was seating in 18F followed a similar course of actions. However, she – a 19-year-old female - cited that congestion in the aisle was her reason for climbing over seats.

The final passenger account of seat climbing behaviour was from a 21-year-old male seated in 20B. He described climbing at least one row of seating en route to the ROW exit. No more details were supplied by this passenger.

In total there were 12 passenger accounts of seat jumping en route to the ROW exit. Of these one – the 14 year old – was more a case of being pulled semi-unconscious over the seating rather than actually deciding to jump the seats. As such she is discounted from the remainder of the discussion. Of the remaining 11 accounts, they were from relatively youthful passengers (ages of 14, 18, 18, 18, 19, 19, 20, 21, 21, 21, 23 and 29) and were from both males and females (eight females and three males). Eight out of eleven of these accounts were from passengers who were seated adjacent to each other and possibly followed the lead of others and chose a similar course of actions.

Table 35: Summary of those passengers that described seat climbing within AASK V3.0 from the Manchester accident in 1985

Seat	Age	Gender	Reason for seat climbing	Exit used	Number of rows climbed
3F	19	FEMALE	AISLE TOO CONGESTED	FORWARD RIGHT	Unknown
6B	21	MALE	QUEUE MOVING TOO SLOWLY	FORWARD RIGHT	Unknown
7E	18	FEMALE	AISLE TOO CONGESTED	FORWARD RIGHT	Unknown
7F	18	FEMALE	ENVIRONMENTAL (E.G. SMOKE)	FORWARD RIGHT	5
9C	42	MALE	UNKNOWN	FORWARD RIGHT	Unknown
9D	18	FEMALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
9E	21	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
11E	21	MALE	SHORTEST ROUTE TO EXIT	RIGHT OVERWING	1
11F	18	FEMALE	AISLE TOO CONGESTED	RIGHT OVERWING	1
14F	14	FEMALE	UNKNOWN	RIGHT OVERWING	Unknown
15A	20	FEMALE	ROUTE TO AISLE BLOCKED BY PAX	RIGHT OVERWING	3
15B	19	FEMALE	ENVIRONMENTAL (E.G. SMOKE)	RIGHT OVERWING	3
15D	23	FEMALE	UNKNOWN	RIGHT OVERWING	Unknown
18E	29	FEMALE	UNKNOWN	RIGHT OVERWING	Unknown
18F	19	FEMALE	AISLE TOO CONGESTED	RIGHT OVERWING	Unknown
20B	21	MALE	UNKNOWN	RIGHT OVERWING	Unknown

Reasons cited by the passengers, were to shorten the route to the exit (3 accounts), to circumvent blockages (3 accounts), and being forced to by the environmental conditions (1 account); the remaining passengers did not specify reasons for their actions. It was difficult to ascertain the exact distance that they travelled over seating, although accounts do indicate that two passengers climbed three seat rows.

Main findings

This aircraft type was not appropriate for aisle swapping behaviour to occur. However, some instances of redirection were reported, all of which were passenger initiated. Indeed the primary reason that they stated for redirecting was that they decided that the current exit was over utilised and that their evacuation could be completed more quickly via another exit. The emphasis in this accident was on the passengers seeking to reduce their own, and their families and friends, personal evacuation times. Thus some passengers redirected from over utilised exits towards other exits within the cabin. This accident supports the view that in accidents involving severe fires passengers tend to make their own decisions regarding the best exits to use.

With respect to seat climbing is apparent that seat climbing behaviour was more common among the youthful. The average age of respondents in AASK V3.0 for this accident is 27.5 years, whereas the average age of those that seat jumped was 21.3 years. Secondly, many of the passengers who were seated adjacent to the exit leaped over the intervening seating. Others attempted to circumvent blockages and/or to gain egress expediency. Finally, similar actions were given by 10 of the 16 passengers who were originally seated adjacent to each other and 13 of 16 were seated adjacent and or in close proximity (within a seat distance of each) to each other. It therefore seems likely that passengers may have copied the actions of another when climbing over seating.

5.4.6.5 Dallas-Fortworth, 1988

On 31st of August 1988, a B727 carrying 101 passengers and 4 cabin crewmembers abandoned its takeoff shortly after rotation. Following a hard landing onto the runway the aircraft over-ran the runway and impacted with the ILS localiser.

The aircraft contained four pairs of exits. From front to rear they were of, Type-I, Type-III, Type-III and Type-I. During the crash sequence the aircraft sustained significant impact damage with the fuselage rupturing in many places. Evacuation was achieved through the FL, FLOW and FLOW exits. In addition some passengers evacuated through forward and aft ruptures in the ceiling the through a rupture in aft left fuselage. The first four rows of seating were configured 2-2; the remaining seating was in the 3-3 configuration. The exit availability, seating layout and location of the ruptures can be seen in Figure 45.

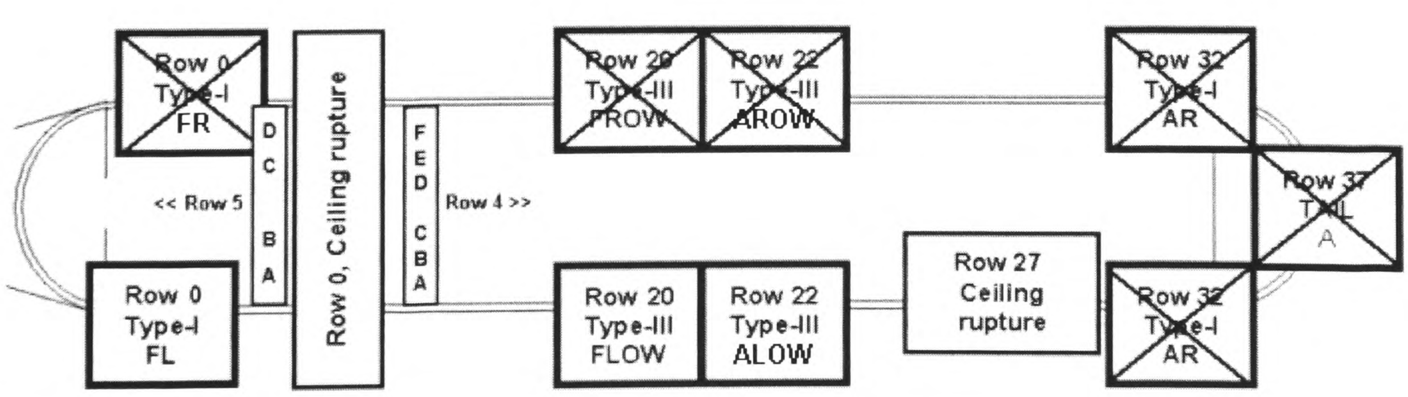


Figure 45: Cabin configuration and exit availability of the B737-222 at Dallas Fort-Worth in 1988 (crossed out exits were unavailable)

During the crash the right wing contacted the ground and caught fire. The fire attacked the aft fuselage and penetrated the aircraft cabin whilst the evacuation was in progress. The accident resulted in the death of 12 passengers and 2 cabin crewmembers. A further 71 passengers and 2 cabin crewmembers sustained injuries. All of the fatalities were attributed to smoke (toxic gas) inhalation.

Conditions within the cabin during the evacuation were hostile. Some passengers commented that they *"could not breath"*, whilst others stated that they suffered reduced visibility and were forced to crawl during the evacuation. The effects of the fire were most severe at the aft portion of the cabin. Numerous passengers reported that debris was obstructive to their evacuation.

In total 88 passenger entries are contained within AASK V3. Of these 66 are based on transcripts reported in various air accident reports and 22 are inferred from the accounts of others.

Events related to crew redirection

a) Passenger accounts

The first passenger account of redirection listed within AASK is from a 30 year old female seated in 20D who assisted other passengers in opening the over wing exit, however she quickly abandoned this choice of exit as flames and smoke entered the cabin through the opening. The passenger evacuated via the FL over wing exit.

A 34 year old male seated in 16A began to evacuate towards the rear of the aircraft however he said that the rear exits were congested with so many people that he headed back towards the front of the aircraft. He finally evacuated through a rupture in the fuselage ceiling.

Another instance of passenger redirection was from a 67-year-old female passenger seated in 18E and a 69 year old male passenger seated in 18F. They decided to switch exits after noticing that other passengers in the aisle were stationary. They both finally evacuated through the AL over wing exit.

A 36 year old male passenger seated in 11A tried to evacuate via the front exit however discovered that it was blocked and so evacuated via a fuselage rupture.

Finally, a 51 year old male passenger seated in 27C tried to exit at the rear of the aircraft, however he found that he could not see and so turned around and helped his step son to evacuate. Both finally evacuated via a fuselage rupture.

b) Crew accounts

Only two cabin crew accounts were available and were brief summaries. As such they contained little information on the evacuation.

Accounts relating to seat climbing

In total five passengers described climbing seats during this accident. Each is described in order of their seat location below.

The first was from a 30-year-old female passenger seated in 1A who stated that she climbed one row of seating. This passenger did not specify her reason. She finally evacuated via the rupture at row one and so may have been moving forwards. This instance was not of a passenger optimising their evacuation route to an exit, but more a case of using the seats as a 'ladder' to evacuate via a ceiling rupture. As such it is not appropriate to the proposed model at this stage.

Another account was from a 38-year-old male seated in 19C who described climbing over one row of seating. He stated that it was the motion of dark smoke towards him that made him decide to take this course of action and as he stated he "dove" over the seating to the FLOW exit.

The next account was from a 24-year-old female seated in 21C. She stated that she climbed over the back of her seat and "hopped" out of the ALOW exit. She did not state her reason for taking this action. This passenger was located in the seat row immediately adjacent to the exit row.

The final account for this accident was from a 38-year-old male seated in 26A. He described climbing over some seats and debris whilst attempting to evacuate via the rupture at row 27. A 27-year-old female seated in 28D described seeing a man climb over seating in order to evacuate via a rupture. Again, this passenger was using seating as a 'ladder' to gain access to a ceiling rupture rather than seeking to reduce his evacuation time to an exit. As such this case is not appropriate to the model at this stage.

Table 36: Summary of those passengers that described seat climbing within AASK V3.0 from the Dallas Fort-Worth accident in 1988

Seat	Age	Gender	Reason for seat climbing	Exit used	Number of rows climbed
1A	30	FEMALE	N/D	RUPTURE 1 (see notes)	1
19C	38	MALE	SHORTEST ROUTE TO EXIT	FORWARD LEFT OVERWING	1
21C	24	FEMALE	N/D	AFT LEFT OVERWING	1
26A	38	MALE	SHORTEST ROUTE TO EXIT	RUPTURE 2 (see notes)	Unknown
28D	27	FEMALE	SHORTEST ROUTE TO EXIT	RUPTURE 2 (see notes)	1

Main findings

No accounts of aisle swapping occurred since this aircraft was narrow bodied. However there were some accounts describing redirection behaviour. The accounts of passengers contained within AASK V3 for this accident indicate that the passengers made their own evacuation decisions during this evacuation. It appears that congestion was the primary reason that passengers stated for redirecting. None of the passengers described hearing cabin crew issue redirection commands during the evacuation.

Four passengers described climbing over seats. Two of these were seated adjacent to the exit row and decided to climb the single seat row in order to gain access to the exit. The remaining two passengers climbed seating to access ruptures in the ceiling. Only one passenger cited a reason for climbing the seats. This passenger stated that the presence of smoke made him decide to hop over the single row of seating that was between him and the exit. Similar to previous accidents passengers who climbed seating were relatively youthful with ages of 24,30,38 and 38. The mean age of passengers onboard the aircraft was 40.2 years whilst the mean age of those that climbed seating was 32.5 years. Half of those passengers that climbed seating were male.

5.4.7 Internal cabin fires

The following accident involved an internal in flight cabin fire. The only accident available in this category was at Cincinnati in 1993. This accident contained accounts relevant to redirection/exit choice behaviour only.

5.4.7.1 Cincinnati, 1983

On the 2nd of June 1983 a DC-9-30 in mid-flight was forced to make an emergency landing following a fire in a toilet compartment panel. The fire was worst at the aft of the cabin where the fire had begun. By the time that the aircraft landed at Greater Cincinnati International Airport, Kentucky, the aircraft cabin and cockpit was full of dense black smoke. Evacuation swiftly followed landing. Remarkably, none of the cabin crewmembers sustained any injuries. However, 23 of the 41 passengers that were onboard were killed and 16 injured; only two passengers escaped injury.

The aircraft had 3 pairs of exits and one tail exit. Front from to rear, they were, a Type-I, Type-III and Type-III. Passengers and crew evacuated through only four of the exits. They were the FL, FROW, FLOW and AROW. Seating was configured in the 2-3 arrangement throughout the aircraft cabin (see Figure 46).

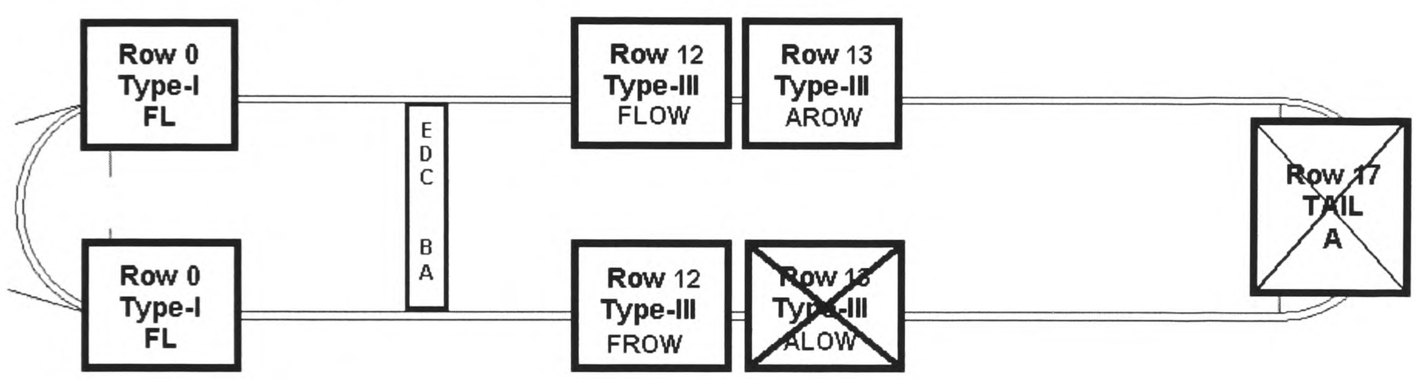


Figure 46: Cabin configuration and exit availability of the DC-9-32 at Cincinnati in 1983 (crossed out exits were unavailable)

The cabin crew had some time to prepare for the evacuation. There activities included the briefing of passengers on exit operation and the redistribution of passengers towards the front of the aircraft where the environmental conditions were less severe.

Environmental condition during the evacuation caused passenger visibility to be almost completely obliterated. Nearly all passengers described the cabin as being filled with dense black smoke. Furthermore, many described its affect as asphyxiating. During the evacuation passengers described the effects of the thermo-toxic environment as causing them difficulty in breathing with some stating that they had to hold their breath, suffering dizziness, severe reductions in visibility with some stating that they suffered eye irritation; some were forced to crawl. In short the cabin conditions were extremely hostile to life. A 34-year-old male commented that the smoke "*hurt the chest*" another man commented *"that his chest burned like fire'"*.

In total there were only 18 passenger entries for this accident contained within AASK V3.0. 14 were based on reported transcripts contained within various air accident reports and four were inferred from the testimonies of others. Only three cabin crewmember entries were contained within AASK. All of these were taken from summary style testimonies.

Events related to crew redirection

a) Passenger accounts

From the AASK database only a few accounts exist in which passengers changed direction.

The first account is from a 39-year-old female seated in 11E. This passenger had intended to evacuate via the right over wing exit, but as she felt her way back through the cabin she could not find an exit. Eventually, she stated that she felt a breeze on her leg. This alerted her to the proximity of another exit. She turned and exited via the FLOW exit. This passenger described the effects of the cabin environmental conditions as causing her difficulty in breathing and seeing.

Another account is from a 28-year-old female seated in 3A. This passenger stated that she initially attempted to evacuate using an aft exit. However, whilst feeling her way aft through the aisle she encountered a passenger moving forwards. She turned around and moved towards the forward exits, finally evacuating through the FL exit. She described the cabin atmosphere as causing her to feel dizzy, suffer eye irritation and have difficulty breathing. Both of these passengers did not report hearing instructions from cabin crew during their evacuation.

A final account was from a 30 year old female who was sat in the centre of the cabin at the start of the evacuation. During the evacuation she moved to the FL exit and took responsibly for managing its use. She also stated that she issued commands for passengers to *"come this way"*. She stated that the passengers complied with these commands. She stated that the atmosphere within the cabin was irritant, dense and that it made her feel dizzy. She stated that she had to feel her way to the front of the cabin. She also stated that she could not see or be seen during the evacuation.

b) Crew accounts

A similar version of events was cited by the 28-year-old female cabin crewmember. Again she was seated in the mid portion of the cabin during the landing. She also felt her way to the front of the aircraft, she stated that *"she was barely able to see due to smoke"* and had to feel her way forward using the seat backs. Once at the exit she took responsibility for its usage.

The 39-year-old senior cabin steward positioned himself between the first row of seats and the bulkhead during the evacuation. He stated that he called instructions during the evacuation. However, he stated that *"there was no noise or conversation during the evacuation"*.

Main findings

No reports of seat climbing behaviour were reported for this accident. In part this may reflect the reduced mobility of the passenger that resulted from exposure to toxic gases prior to and during the evacuation. With respect to aisle swapping behaviour, this aircraft type was not appropriate for aisle swapping to have occurred.

There were however some reports of redirection. From these it is interesting to note that none of the passengers stated that they heard the commands of any of the cabin crewmembers during the evacuation. However this could be an artefact of their testimonies rather than actual events as numerous passengers invested much of their testimonies describing the events prior to landing in more detail rather than those of the evacuation itself. From the testimonies of passengers and crew it appears that little or no redirection occurred in this accident. The main reason stated for passengers changing their direction during the evacuation was that they had inadvertently passed an exit or met somebody walking in the other direction. Recall that visibility was completely obliterated forcing all evacuees to feel their way through the cabin. Whilst cabin crewmembers stated that they issued commands only one of the passengers stated that they heard them. Conclusions from this emergency evacuation are that dense smoke obliterates vision and makes movement extremely difficult. Given that movement is a time consuming business redirection would become a very unattractive option.

5.4.8 Discussion

5.4.8.1 Redirection

This investigation has revealed a relatively large number of descriptions of redirection events and features that require representation in a mathematical model of the process.

From, the accounts contained within AASK it is apparent that all forms of redirection are based on an assessment of the current situation within the aircraft cabin and so change as the scenario evolves. Thus, models used to represent the passengers and crew should allow them to assess their environment throughout the simulation. Indeed, this investigation provides evidence to suggest that the stimulus to a redirection event is a change to the environment/scenario, i.e. changes to exit availability, congestion levels within the cabin or environmental conditions. Any model that is developed should take this into account.

A further finding of this work is that that redirection behaviour in emergency evacuations is relatively frequent. However, the data examined suggests that in scenarios without fire the behaviour of passengers was quite different to those in which fire was present. Indeed some differences were also observed between 90-second certification trials and real emergency evacuations that did not involve fire. Simplistically behaviour are grouped into two broad categories that define their characteristics,

- non-fire/external fire scenarios, and
- burn-through/internal fire scenarios.

As with 90-second certification trials, in the non-fire cases it was apparent that cabin crewmembers were able to redirect passengers to alternative exits with relative ease and that the majority of passengers appeared to do as instructed. Only a few instances of passengers disobeying the commands of the crew were present within AASK. However, when disobedience was observed it involved the passenger(s) deciding that they had a better evacuation route than that proposed by the crew. These differences are however small with the accounts reviewed in this thesis indicating that passengers were marginally less subservient to crew instructions in real emergency evacuations even those that did not involve fire or involved external fires.

Another finding of this investigation is that in non-fire and external fire evacuations passengers sometimes chose to redirect themselves. This type of behaviour is occasionally witnessed during 90-second certification trials, however it is rare - in 90-seconds certification trials passengers generally do as instructed by the crew. In order to model redirection in non/external fire emergency evacuations it is necessary to have a form of passenger-initiated redirection. In other words there is a requirement to develop a model to represent passenger exit choice. Such a model should simulate passengers' attempts to find the shortest personal evacuation time.

Another feature of non/external fire scenarios was that passengers who were finding their own evacuation routes were generally willing to abandon their plan and obey orders from cabin crew when instructed. A model to simulate real emergency evacuations should incorporate this feature in non-fire or external fire scenarios.

The accounts of passengers and crew from accidents involving severe fires that penetrated the aircraft cabin were very different to those in which fire was absent or an external fire was present. Firstly, in burn through fire scenarios passengers were extremely insubordinate to crew instructions. It could not be determined whether this was due to an inability to hear instructions or simply electing to ignore instructions. Either way, the net result was that the passengers were very unlikely to obey crew commands. Secondly, the presence of a thermo-toxic atmosphere greatly affected the ability of the crew when collecting dynamic information. Very often in fire cases the visibility in the cabin was not conducive to vision at all. Any model should have a mechanism of representing the limiting effects that smoke has upon vision. Also the ability of the crew to communicate instructions to passengers was also extremely reduced in burn through scenarios. Any model of real emergency redirection behaviour should have a mechanism of representing reduced communication effectiveness.

5.4.8.2 Aisle swapping

Unfortunately there is very little evidence on which to base conclusions. Only one definite report of aisle swapping of the type defined earlier was present within the accounts contained in AASK. However, its absence does not mean that aisle swapping simply does not occur in real emergency evacuations but may indicate that it is not considered important enough to warrant description in post accident testimonies. The development of a model in this work will then be primarily based on the visual evidence from video footage of 90-second certification trials. That said, it is not unreasonable to assume that aisle swapping would occur with a frequency at least equal to that witnessed during 90-second certification trials. In addition, similar to redirection it is possible that during highly charged evacuations such as burn through scenarios passengers may be more likely to consider alternative strategies and swap aisles. Some representation of these features is considered desirable for a model.

5.4.8.3 Seat climbing

Overall citations of seat climbing behaviour in passenger accounts are relatively low with approximately 1 out of 20 passengers describing seat climbing behaviour. The majority of citations come from accidents that involved cabin burn through. The reason for this is somewhat unclear. A possible interpretation is that passengers are more likely to climb over seating in accidents that involve a fire threat and a potential entrapment situation. However, conclusions should be tempered by the fact that more detailed reports were available for input into AASK from burn-through accidents, as such a higher frequency might be expected.

A further finding of this investigation is that the majority of seat climbing descriptions originated from only three narrow-bodied aircraft accidents. This may suggest that once someone has begun to climb seating others are likely to follow a similar course of action. This conclusion is strengthened by the accounts of passengers who were sat adjacent to each other describing similar actions during the evacuation. This is more clearly seen through plotting the seat locations of those passengers that seat climbed (see Figure 47). It can be seen that many passengers who seat climbed were sat adjacent to each other (solid rings) or within one seat of each other (dash rings). Also from Figure 47 it can be seen that much of the seat climbing behaviour were instances of passengers climbing a single seat row adjacent to a Type-III over-wing exit.

Only 3 seat climbing accounts originate from accidents involving wide-bodied aircraft. All of which would be classed as non-severe emergency evacuations, i.e.

burn-through did not occur. This reflects the lack of severe wide-bodied aircraft evacuations involving burn-through or internal fires contained within AASK. The closest accident involving a wide-bodied aircraft was that which occurred at John F. Kennedy Airport in 1995. However whislt this accident suffered burn-through, it occurred only once the passengers had evacuated the aircraft. Of the three accounts, from non-severe wide-boided accidents two referred to aisle swapping and seat climbing and did not specify the number of rows that were climbed. Only one of the accounts actually cited the number of rows that were climbed (13 rows). As such there is little available data on seat climbing in severe emergency conditions on wide-boided aircraft.

Finally, the gender of passengers that did decide to climb over seating was mixed; however the ages of passengers that climbed over seating was skewed towards the youthful. This suggests that the young are more likely to climb over seating then the elderly.

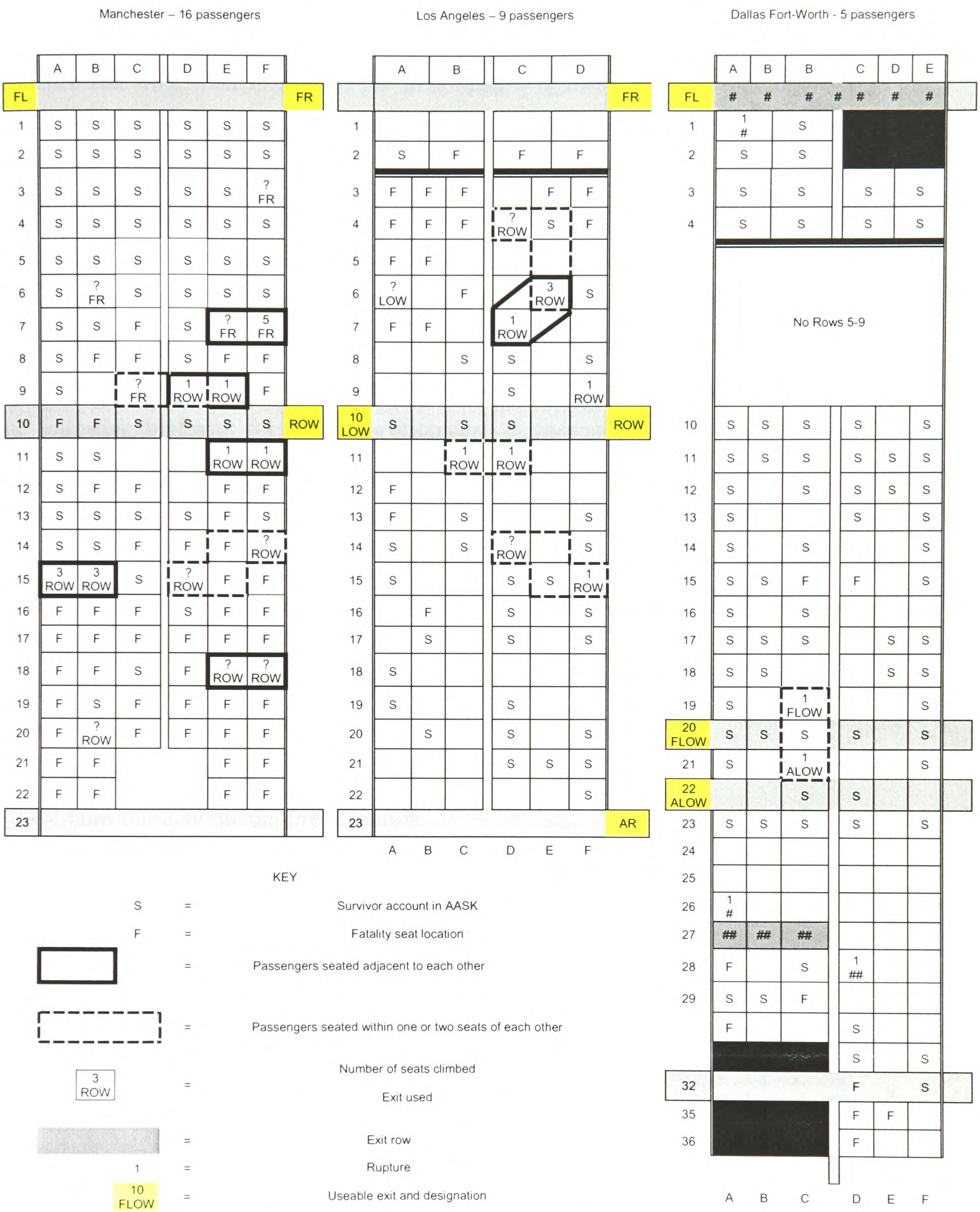


Figure 47: Seating locations of seat climbers from Manchester 1985, Los Angeles, 1991 and Dallas Fort-Worth, 1988

5.5 Concluding remarks

The investigation in this chapter has to some degree answered the question *"What evidence can we collect to support the development of these behaviours?"* and has also provided some understanding of the mechanisms and processes involved in these behaviours.

In doing so a blueprint for answering the final two questions raised in this thesis can be addressed, namely, "How can the results and behavioural capabilities of the model be improved?" and "How can the behavioural capabilities of the model be extended to cover the range of behaviour witnessed in real accidents scenarios?" In this context the following blueprint for model development to answer these two questions is proposed.

Firstly this study suggests that behavioural characteristics during emergency evacuation can be categorised into three broad groups for the development of a model, they are,

- 90-second certification trials
- non-fire/external fire scenarios, and
- burn-through/internal fire scenarios.

Crew redirection was frequently witnessed in every category, although its effectiveness differed according to the scenario. In contrast passenger seat climbing was most frequent in burn-through scenarios and barely witnessed in other types of evacuations. Curiously accounts of aisle swapping were absent from non/external and burn-through fire scenarios. This is thought to originate from passengers considering it of minor detail when filling questionnaires.

The principle mechanisms that are involved in these behaviours are,

1. the collection of information,
2. the processing of the information, and then
3. the actioning of any decision based on the above,

and are similar across the three scenario categories. However, the effectiveness and outcome of each aspect varies according to the scenario/category. Any model should consider the three processes, their influences and effectiveness in the context of the three scenario groups. This should enable the trends of the three scenarios to be modelled accurately. The next two chapters document the development of models based on this blueprint.

6 A Decision Making Model for Passenger and Crew Exit Choice

This chapter details the development of models to represent crew intervention during evacuations based on the analysis of previous accidents and 90-second certification trials from the previous section. Before, describing the model it is necessary to appreciate the dilemma that is faced by mathematical modellers of human behaviour.

When developing computer based models of human behaviour we are confronted with either lack of scientific understanding of the process involved or limitations imposed by current computational resources. Thus a degree of abstraction is nearly always required. However this must be tempered by the requirement that the model realistically represents the processes involved.

Conceptually, mathematical models of human behaviour exist within a continuum. At one end of the continuum lies a model that exactly represents the human decision making process. This is unlikely to be achieved due to limitations in scientific understanding and computational resources required to simulate them. At the other end of the continuum lies a simplistic mechanistic model of human behaviour that only consider the mechanisms involved with movement and virtually ignore all decision making. The need for realism prohibits models at this end of the continuum also. Thus, realistic mathematical models of human behaviour inhabit the middle ground and attempt to balance the need to represent the human processes via the use of mathematically derived approximations based on appropriate abstractions from current scientific understanding.

6.1 The development of models to represent passenger exit choice and crew initiated passenger bypass

6.1.1 A model for cabin crew passenger direction during 90-second certification trials

An understanding of the required features of a crew redirection model for use in 90-second certification trials was developed in the previous chapter. The proceeding sections describe the development of a mathematical method of representing this crew procedure. Prototypes of the model are then employed within the airEXODUS framework.

The crew redirection models that are developed are designed to simulate a crew member stood relatively close to an oversubscribed active exit and bypassing passengers either forwards or backwards to another. Three examples of the type of scenario the crew direction model attempts to solve are shown in Figure 48. In each example a crew may be required to redirect passengers to other exits (indicated by the arrows). It is apparent from these three examples that redirection could occur in a range of different scenarios and configurations.

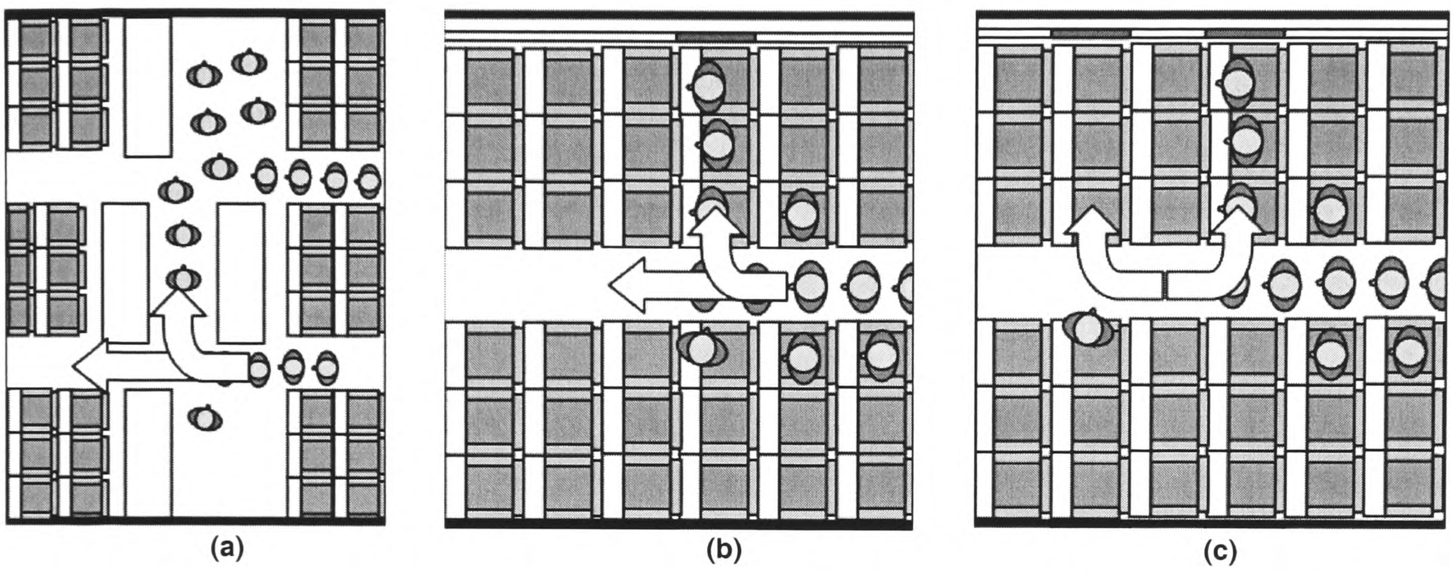


Figure 48: Three example scenarios that the crew initiated redirection model attempts to simulate

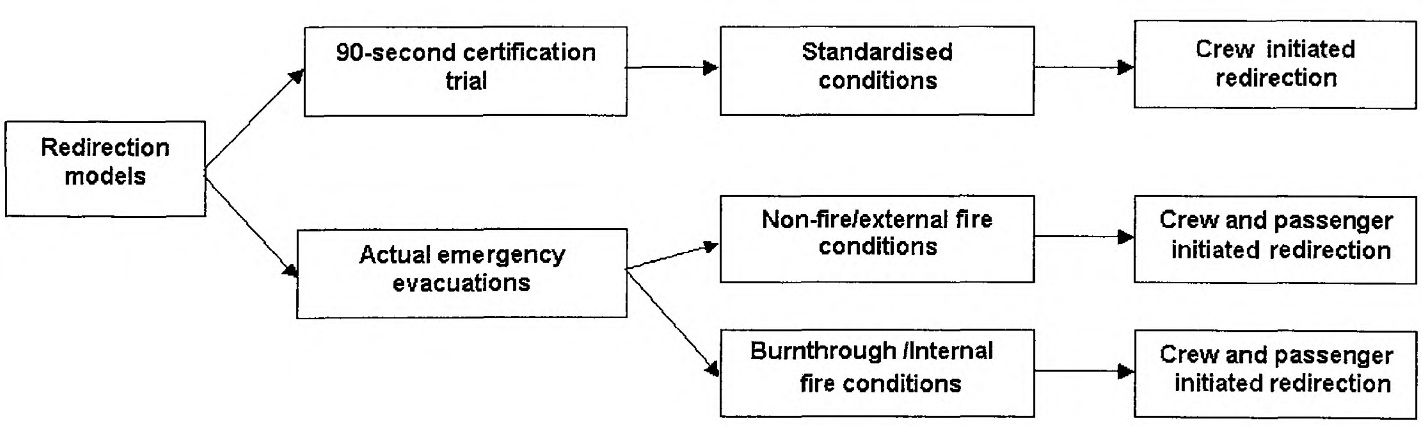


Figure 49: Redirection models that are developed

The complexity of behaviour exhibited during emergency evacuations can be viewed as a continuum in which a relatively small behavioural sub-set is produced during 90-second certification trials and a more complex and extensive behavioural sub-set occurs during highly stressed real emergency situations. As such the development of models is tackled incrementally, beginning with the simplest set of behaviours (i.e. 90-second certification trials) and then extending the model to cover more complex scenarios (i.e. real emergency evacuations). Based on the findings of the previous chapter, three sub-variations of the redirection models are developed (see Figure 49). Each model represents a different layer of behavioural complexity and so the number of features that are required in order to model the process is extended in each case (see Table 37).

Table 37: A Summary of the required features of passenger and crew redirection models according to the type of scenario

90-seconds	Non-fire/External	Burn-through/Internal fire
▪ Seek to optimise evacuation of **aircraft as a whole** ▪ Explicitly represent crew ▪ Allow different redirection stations ▪ Provide a means for crew to assess evacuation efficiency ▪ Support dynamic information gathering through vision ▪ Support verbal/gesture communication ▪ Support touch communication ▪ Provide mechanism for crew fallibility	▪ This model is sensitive to the "STATE" of the evacuation, i.e. non-fire/external fire or burn-through/internal fire ▪ Seek to optimise evacuation of **aircraft as a whole** ▪ Explicitly represent crew ▪ Allow different redirection stations ▪ Provide a means for crew to assess evacuation efficiency ▪ Support dynamic information gathering through vision ▪ Support verbal/gesture communication ▪ Support touch communication ▪ Provide mechanism for crew fallibility	▪ This model is sensitive to the "STATE" of the evacuation, i.e. non-fire/external fire or burn-through/internal fire ▪ Seek to optimise evacuation of **aircraft as a whole** ▪ Explicitly represent crew ▪ Allow different redirection stations ▪ Provide a means for crew to assess evacuation efficiency ▪ Support dynamic information gathering through vision ▪ Support verbal/gesture communication ▪ Support touch communication ▪ Provide mechanism for crew fallibility ▪ Provide a mechanism for smoke visibility effects on dynamic information gathering ▪ Crew should take smoke conditions into account when determining egress routes and optimality ▪ Reduce effective communication range
▪ Passengers always do as instructed	▪ Passengers nearly always do as instructed ▪ Provide passengers with mechanism to assess / determine the **best exit for them personally** ▪ Passengers gather dynamic information throughout the simulation ▪ Provide a representation of passenger visibility	▪ Passengers nearly always do as they want ▪ Provide passengers with mechanism to assess / determine the **best exit for them personally** ▪ Passengers gather dynamic information throughout the simulation ▪ Provide a representation of passenger visibility ▪ Provide a mechanism for smoke visibility affects on dynamic information ▪ Passengers should take smoke conditions into account when determining their egress route

6.1.1.1 Modelling the crew bypass process

From the analysis of video footage of the redirection procedure, it was apparent that the first aspect of the model is for the crewmember to move to the designated redirection station within the cabin. Whilst the basic mechanics of simulating movement are well understood within evacuation modelling, additional analysis of video footage was required in order to understand and then model the unique nature of crew/passenger confluence. From the analysis of 90-second certification trials it was clear that the crew move throughout the cabin with relative ease and passengers are cooperative to the wishes of the crew. Within the model crew always win conflicts for space, however a small penalty should also be applied to their unimpeded movement speed to represent the relative awkwardness of squeezing past other passengers.

Each individual cabin crewmember is usually only responsible for a certain number of exits. However, as the evacuation unfolds the crew may move to other passenger direction stations and in doing so adopt/relinquish control of certain exits. In reality a crew that has more than one redirection station during the evacuation each have responsibilities for many exits, however during the evacuation each crewmember would concentrate on those that are specific to his/her current location/role.

As such, from an 'object orientated' perspective it was decided that exit responsibility should be considered as a property of the redirection station rather than the crewmember. This approach has advantages, primarily with respect to flexibility as it allows the role of crewmembers to change during the evacuation.

Within the model a crew first occupies a particular redirection station and takes the appropriate role and exit responsibilities for the station and the redirection process is initiated. The passenger direction process is concluded within the model when the crew determines that passengers in his/her assigned areas of responsibilities fall below some arbitrary threshold value. If the crew member was directing passengers until the completion of the evacuation this would be until the cabin is completely empty, i.e. a threshold of zero. It is recognized that in reality the cabin crew would use a range of criteria for determining when to cease redirection procedures. For example, they may cease redirection once a reasonable balance between exits is perceived and/or for a specified period of time has elapsed. At present a threshold value of zero, i.e. the cabin must be completely empty, has been employed within the experimental prototype. Extending the prototype to include the additional methods is of minor technological difficulty and is left for future work.

Based on the analysis of video footage and crew interview transcripts a summary of the decision making process of crew in real 90-second certification trials is now described. When performing the redirecting procedure the cabin crew constantly assesses passenger flow patterns and conditions within the cabin. In doing so they would use their judgement to determine whether one exit will cease evacuating before another. They may consider factors such as which exits are moving more quickly than others and the number of users of each exit. In essence the crew member is performing a simple flow rate calculation in their head based on their intuitive knowledge of the aircraft and the events within the cabin.

If the cabin crewmember determines that there may be a problem, then they consider redirecting a passenger. At this stage it is necessary for the cabin crewmember to determine whether redirection would reduce the scale of the problem or alleviate the problem completely. This involves the crewmember assessing the impact of redirecting passengers, i.e. do they think redirecting will help or hinder the evacuation. This process also involves the crewmember selecting passengers to redirect who would best help to alleviate any imbalance in exit performance. In essence this involves assessing another flow rate calculation in which they presume that certain passengers would use the alternative exit and recalculate the finishing times of the exits accordingly. The final stage of the process involves the cabin crewmember communicating their instructions to passenger(s).

The flow diagram presented in Figure 50 summarises the sequence of events previously described and will serve as the basis of the prototype model. The prototype models that are developed in this chapter reflect this process. Within the prototype models a crew member will be given knowledge of the flow rate capabilities of the exits and the exits that the passengers are going to use. Using this information a determination can be made on whether redirecting a passenger from an overloaded exit to one that is undersubscribed would expedite the evacuation of the aircraft. This will take account of the flow pattern within the cabin and will use a rudimentary scheme for simulating the vision of crew. Having determined that it is beneficial to redirect a passenger, further algorithms are provided to simulate the communication of commands and the passenger's response to them. Each aspect of the model will be described in more detail in the following sections.

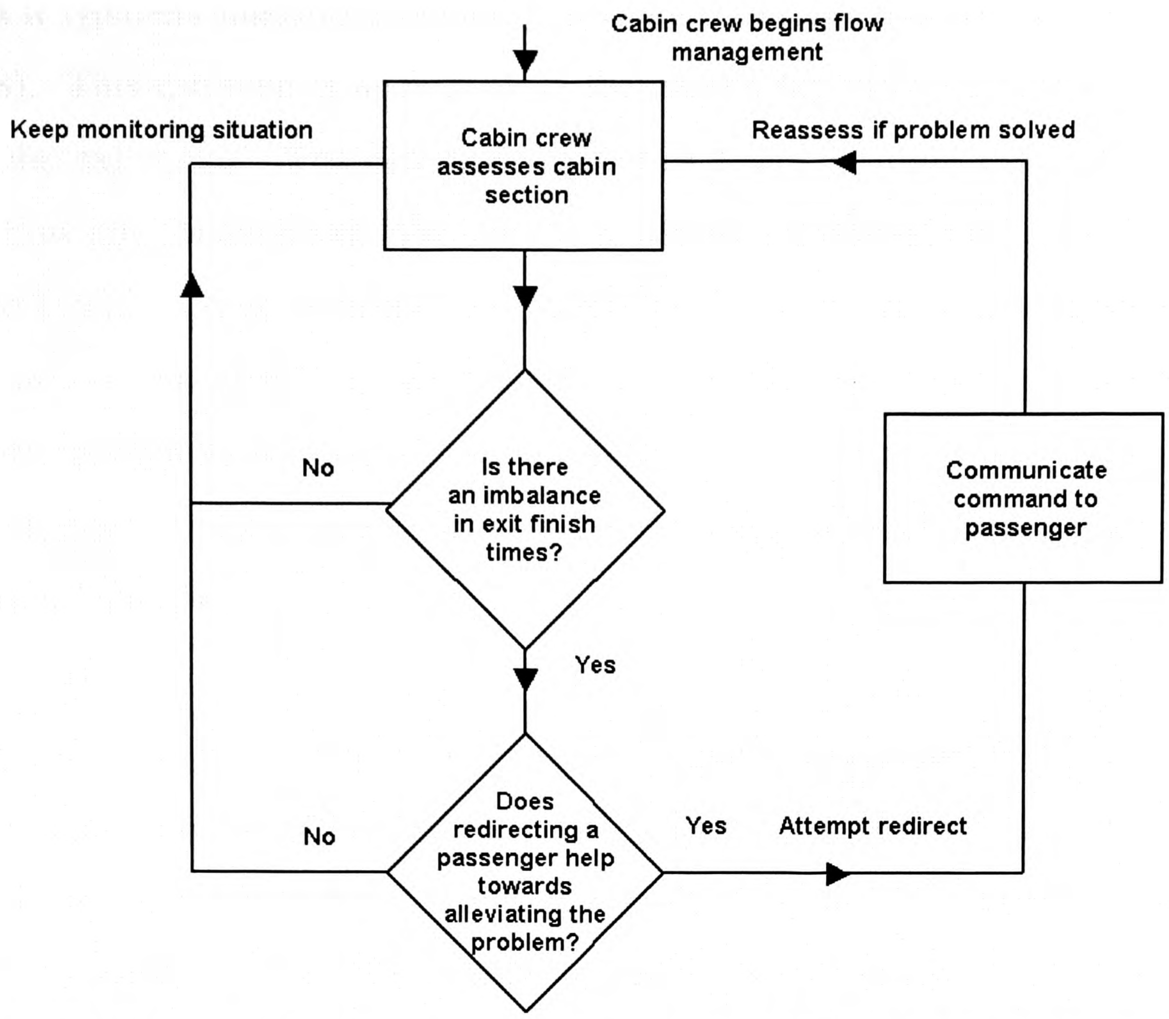


Figure 50: Abstract flow diagram of the cabin crew model when redirecting passengers

Assessing the finish time of exits

According to Figure 50 the first step for the cabin crewmember is to determine whether there is an imbalance in the time that each of the exits for which they have responsibility will cease evacuating passengers. This involves forming an estimate of the likely finish time of the exits. This process is complex, involving a judgment of numerous factors such as the size of the exits, number of passengers using each exit, the likely exit choice of those passengers, their movement speeds, the nature of the queues within the cabins i.e. continuous or segmented. Given this complexity it is necessary to simplify the process to those aspects that are most vital to a model and capable of capturing the qualitative trends witnessed in 90-second evacuations.

Table 38: Static crew estimate (f_i)of the time required to evacuate a single passenger through each exit type

Exit Type	Time required to evacuate a single passenger (seconds)
Type-A	0.56
Type-B	0.91
Type-C	0.94
Type-I	1.04
Type-III	1.65

The method adopted for estimating the likely finishing time of exit uses the flow capability of the exit and the number of passengers that are thought to be using it. It is not considered unreasonable to expect trained cabin crew to know that a Type-III exit would generate a much lower flow rate than a Type-A exit. This knowledge is represented through providing simulated cabin crew with an estimate of the amount of time that it typically takes to evacuate a passenger through each of the exit types (see Table 38). This estimate is analogous to the crew's perception of the capabilities of each of the exit types. The estimates shown in Table 38 were calculated using the average flow rate for each exit type and are indicative of general performance levels for their type [158]. These estimates will uniformly provide the crew with an extremely accurate assessment of the average flow rates through exits. However, in reality their judgement may not be so accurate and individuals' assessments would vary. To more realistically model these factors some error can be introduced into the static flow rate estimates in Table 38.

The number of passengers who will use each exit is considered as being dynamic information and thus should be collected by the crew throughout the evacuation. Two approaches to representing this information are proposed. The first approach gives cabin crewmembers a complete information set with regards to the location of passengers during the evacuation. The Total Dynamic Information Set (TDIS) method allows the cabin crewmember to know the exact location of every passenger onboard the aircraft at all times. This represents an optimal situation bestowing crew with complete visual access of their environment and as such does not represent the actual information gathering capabilities of the crew. The second implementation, Line Of Sight Information Set (LOSIS), limits the knowledge of the cabin crewmembers according to their line of sight.

Computationally, line of sight calculations are very expensive. Thus, within the experimental prototype model functionality has been developed for the user to manually define visibility regions specific to the location of the crewmember. Since redirection only occurs from specific redirection stations visible regions need only be supplied at the redirection stations. This limits the effort that a user must expend in defining visibility within the cabin whilst also avoiding the computational expense of line of sight calculations. Furthermore the approach is flexible allowing input from specific visual access software or experimental studies. Independent of the implementation, limiting dynamic information gathering to that of line of sight or visual accessibility is a more realistic method of representing dynamic information gathering within evacuation models. Both the TDIS and LOSIS approaches have been implemented within the prototype.

At this stage a simplistic estimate of the likely finish time of each exit for which the crew is responsible for is calculated using Equation 13. Considerations for passenger movement are dealt with later.

$$T_i = p_i f_i \tag{13}$$

i = an exit from the list of exits that the crewmember is responsible for and monitoring, i.e. R1, L1, R2....

T_i = clearance time of exit $_i$

p_i = the number of passengers thought to be using the exit $_i$

f_i = an estimated amount of time required to evacuate a passenger through exit $_i$

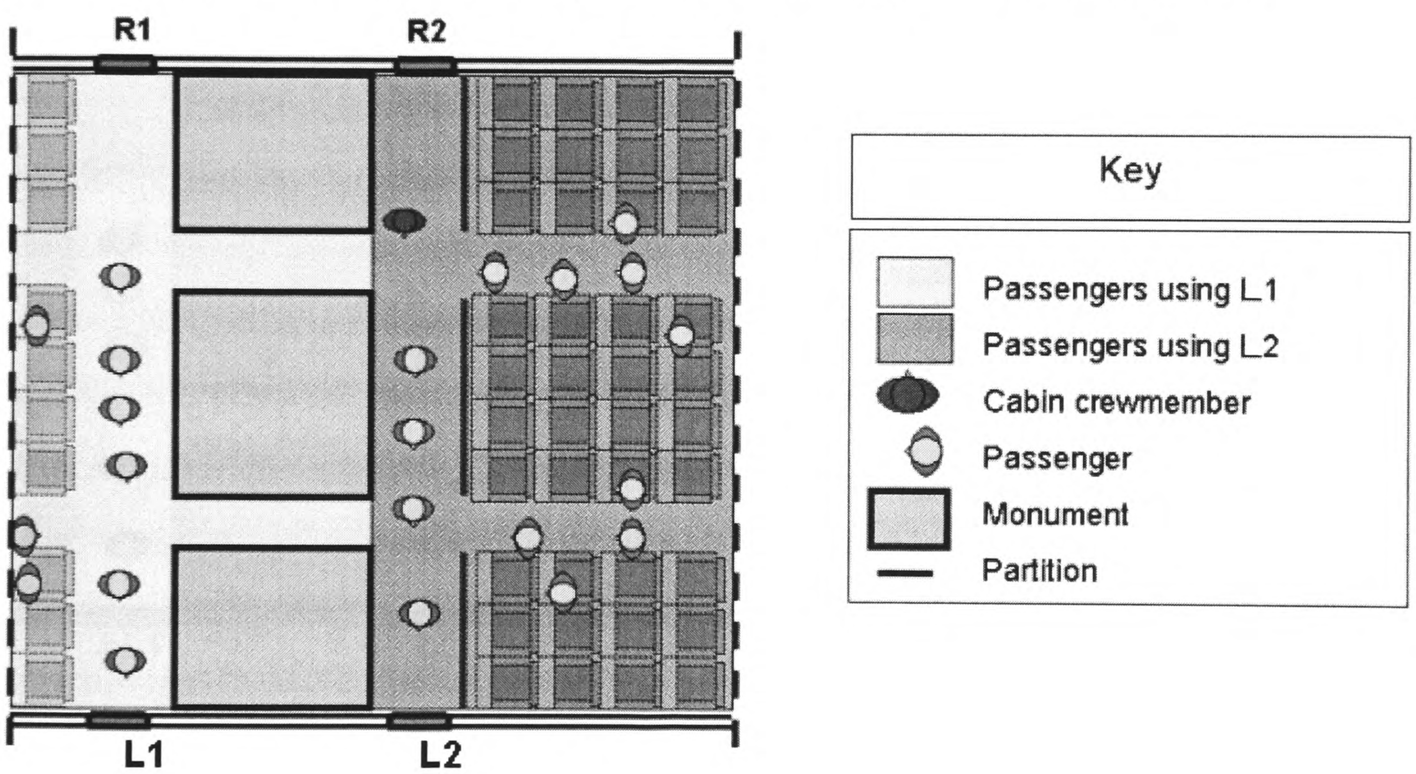


Figure 51: Hypothetical cabin section showing how a crewmember using the total knowledge implementation would ascertain the number of passengers likely to utilise each exit

Using the TDIS method of information gathering, the number of passengers (P_i) that would be counted as using each exit is determined according to the area of the cabin section in which they are positioned, i.e. the potential well catchment areas for each exit, and the flow pattern within the cabin, i.e. their preferred exits. This is explained through a graphic example (see Figure 51). Figure 51 shows a hypothetical cabin section that has two Type-I exit pairs of which only the left side are operable. A cabin crewmember is positioned within the vestibule area of the R2 exit and is monitoring the flow of passengers to the two active exits, L1 and L2. Given the scenario illustrated in

Figure 51, the prototype model would conclude that 9 passengers are likely to use the L1 exit whereas 13 passengers are likely to use the L2 exit.

Within the model an estimate for the likely amount of time required to evacuate a passenger through a Type-I exit (f_I) under 90-seconds certification trial conditions is set to 1.04 passengers/second. This number represents the average exit flow rate of this type of exit during 90-second certification trials (see Table 38). Equation 13 using Figure 51 as an example produces an estimated time of 9.4 seconds for exit L1 and 13.5 seconds for exit L2. In this example it is estimated that there is an imbalance of passengers between the L1 and L2 exits that amounts to 4.2 seconds.

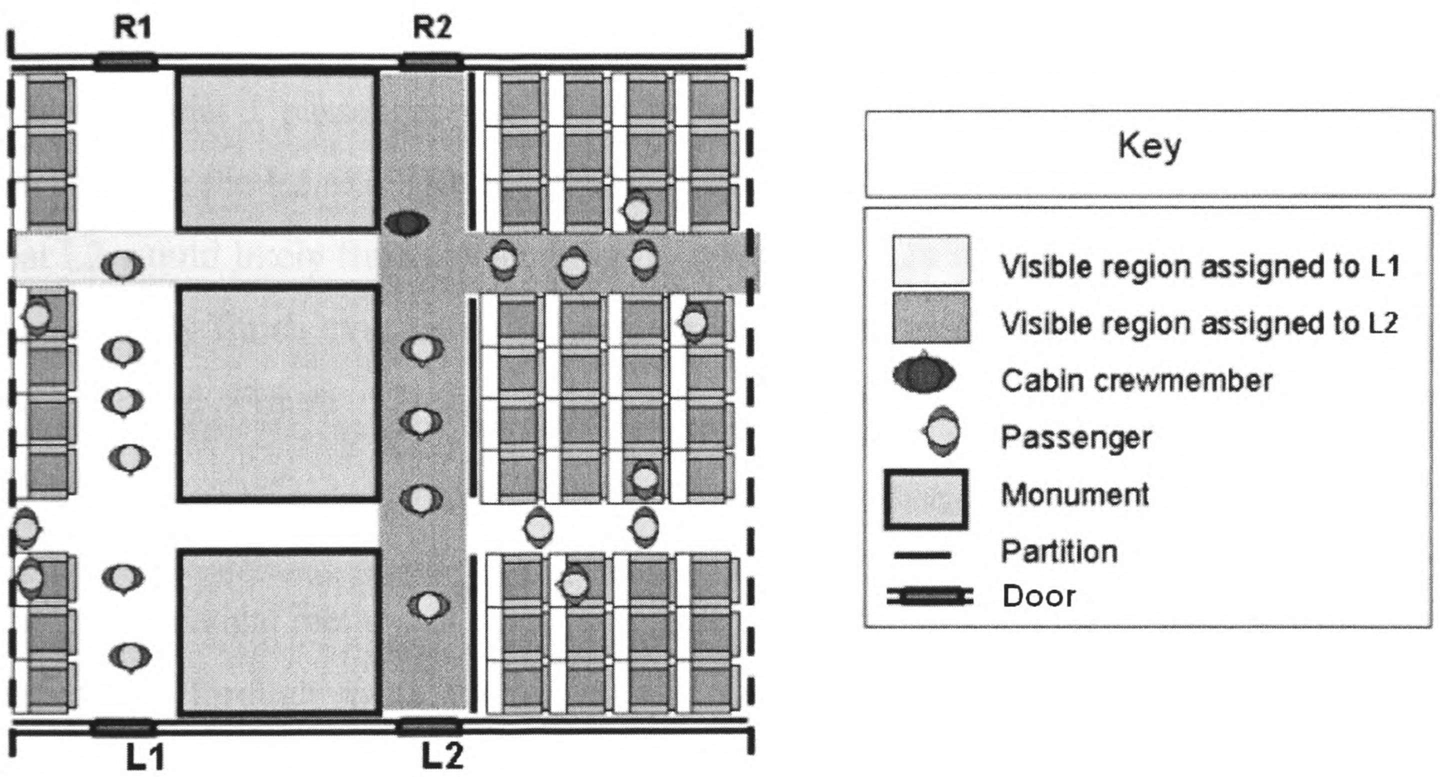


Figure 52: Hypothetical cabin section showing how a cabin crewmember may visually ascertain the number of passengers likely to utilise each exit using the visual accessibility method

Within the prototype model, functionality has been included so that the amount of visual information that is available to cabin crew when performing bypass is restricted. Figure 52 shows the same cabin section as Figure 51, however in Figure 52 the visible region has been defined for the crew direction station. Once defined, the cabin crew can only see passengers that are located within the visible region for their redirection station.

The visible regions approach essentially imposes a stencil onto the geometry that prohibits vision of areas that not contained within the stencil, i.e. those areas that are not visible (see Figure 53).

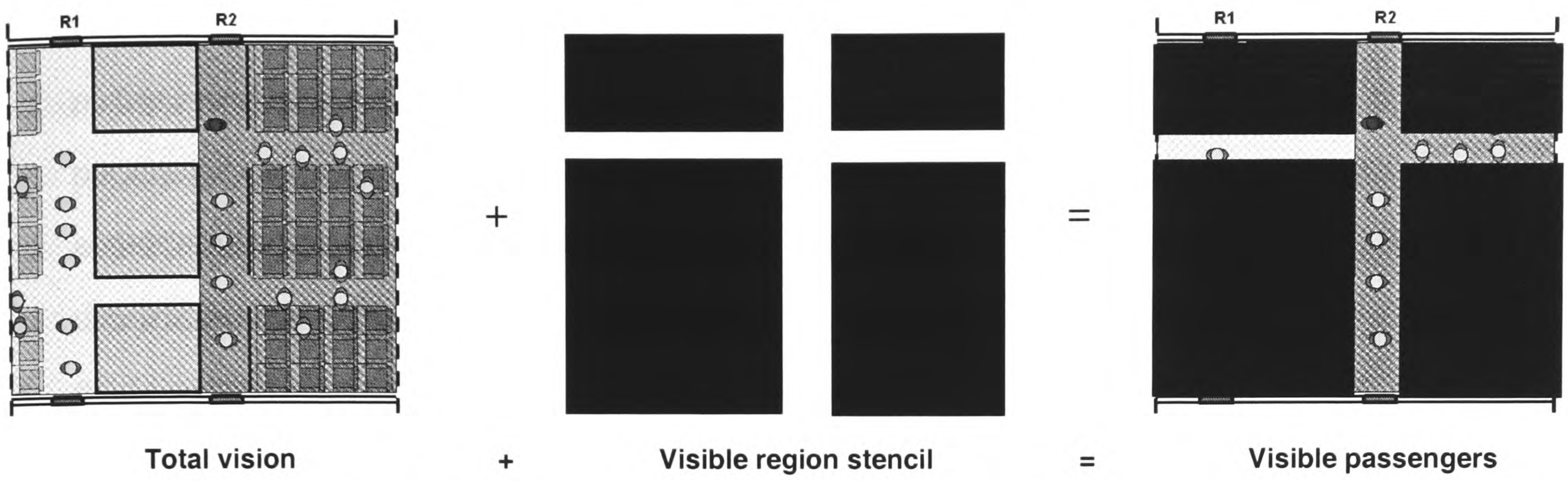


Figure 53: The use of a hypothetical stencil to limit visual access during the evacuation

The impact that this would have is seen through revisiting the hypothetical scenario defined in Figure 51. It can be seen that using the visible regions defined in Figure 52, the crew member's vision is somewhat hampered by the location of partitions, monuments and seats. Using the visible regions, the cabin crewmember would determine that 1 passenger was likely to use the L1 exit and that 7 passengers were likely to use the L2 exit. Recalculating Equation 13 using the visible regions indicates that L2 would likely finish evacuating passengers in 7.28 seconds, however the L1 exit would likely finish evacuating passengers in 1.04 seconds. Using the visible regions method (see Figure 52) the imbalance cause simulated crew to form different conclusions.

The mathematical method of determining the imbalance in the time required to evacuate passengers through exits for which the crewmember is responsible can now be formalised. An imbalance of passengers (T^I), is calculated by the crew member at every second via subtracting the best finish time of the exits (T_{best}) from the worst finish time of all exits (T_{worst}), see Equation 14. If an imbalance is sufficiently large then the cabin crewmember is alerted to the fact that redirecting some passengers away from the exit with the longest time to clear (T_{worst}) may be needed.

$$T^I = T_{worst} - T_{best} \qquad 14$$

T^I = an estimate of the imbalance between exits

$T_{best} = \min \{T_{L1}, T_{R1} \ldots T_n\}$ i.e. the best clearance time of the cabin crewmember's exits

$T_{worst} = \max \{T_{L1}, T_{R1} \ldots T_n\}$ i.e. the worst clearance time of the cabin crewmember's exits

n = the total number of exits

Just what constitutes a sufficiently large difference would vary according to the ability of the crew to judge when an imbalance exists. This is modelled via the use of a new parameter called 'judgement' and represents crewmembers' perception abilities. The actual value used is not important so long as it prohibits the crew having the ability to determine tiny differences in exit finishing times, i.e. differences in the finishing times of 1 second, 0.2 seconds or 0.01 seconds, and smaller. Within the experimental prototype the value is arbitrarily fixed at 5 seconds. Within the model the judgement attribute is used to determine whether any difference is perceptible thus,

$$[\, T_{best} - T_{worst} \,] < \textit{judgement} \rightarrow \textit{NO recognisable difference} \qquad 15$$

Should a cabin crewmember have determined an imbalance between the likely finish times of their exits then the next stage for the cabin crewmember is to consider some form of passenger bypass.

Redirecting passengers

This section describes a model of how the crew may redirect a passenger to another exit in order to alleviate an imbalance in the likely finish times of exits. Within the prototype model the cabin crewmember will only consider the redirection of those passengers that are currently positioned within communication range and a visible region. More complex situations in which a cabin crewmember has to move in order fetch passengers or communicate with other cabin crew are the subject of future work.

When considering passengers that are within communication range, the cabin crewmember is primarily concerned with moving passengers from the exit that is going to finish evacuating passengers last, i.e. the exit that is responsible for T_{worst} towards the exit that is going to finishing evacuation passengers first, i.e. the exit that is responsible for T_{best}.

Furthermore the crew would exclude some passengers who are perceived to be unable to react to her command within a reasonable amount of time. Passengers that are unbuckling seat belts or waiting in seat row congestion are not appropriate candidates for redirection as they are not in a position to respond to any crew command. This is realised within the experimental prototype by limiting passengers that are considered for redirection to those that have: a) responded to the call to evacuate and b) are located within open terrain, i.e. aisles, cross aisles or vestibules.

Presuming that there are appropriate candidate passengers for redirection within their area of influence, a cabin crewmember would select passengers who are best placed for redirection to the new exit, i.e. the exit that will finish evacuating passengers the soonest (the exit responsible for T_{best}). Primarily their assessment would be limited to those who they can communicate with, i.e. those that are within their range of communication and are visible. The crew further considers the flow pattern within the cabin and the length of time that it will take the passenger to reach the alternative exit, this is dealt with in a later section of this chapter.

Firstly methods of calculating the time for a passenger to reach each exit that takes into account the flow pattern within the cabin are developed. These methods are used to determine passengers that are best placed for redirection through ranking the candidate passengers in order of the length of time it will take them to reach the exit. This provides the crew with a mechanism for choosing which passenger to redirect. To do this, the cabin crewmember first estimates how long it is likely to take the passenger to reach the alternate exit if the passenger were redirected. This is calculated from knowledge of the passenger's movement velocity (v_i), adjusted according to the terrain that the passenger will traverse and the distance that the passenger is located from the exit (d_i). Further adjustments for environmental conditions are considered in a later section.

$$t_{i,best} = \frac{d_{i,best}}{v_i} \qquad 16$$

t_i = the passenger under consideration

t_{best} = the exit responsible for generating T_{best}

v = the velocity of the passenger $_i$

d = distance for passenger $_i$ to the alternative exit $_{best}$

t = time for passenger $_i$ *en route* to exit $_{best}$

As with the estimate of the clearance time this approach bestows the crew with exceptional abilities when determining how long it will take the passenger to reach an alternative exit. Again this represents an unrealistic situation, as the crew would not be able to exactly know the movement speeds of the passengers or the exact length of the evacuate route. This is addressed through the introduction of errors or 'fuzziness' into their assessments. In this way the crew can only approximate the movement speeds of the passengers and the length of the evacuation route. This is discussed in more detail later.

A key assumption of this approach is that the route that the passenger has to travel is free from other passengers. Obviously this is not always the case. Therefore, the model should have the cabin crewmember scan the path that the redirected passenger has to traverse to reach the alternative exit to assess the flow pattern within the cabin.

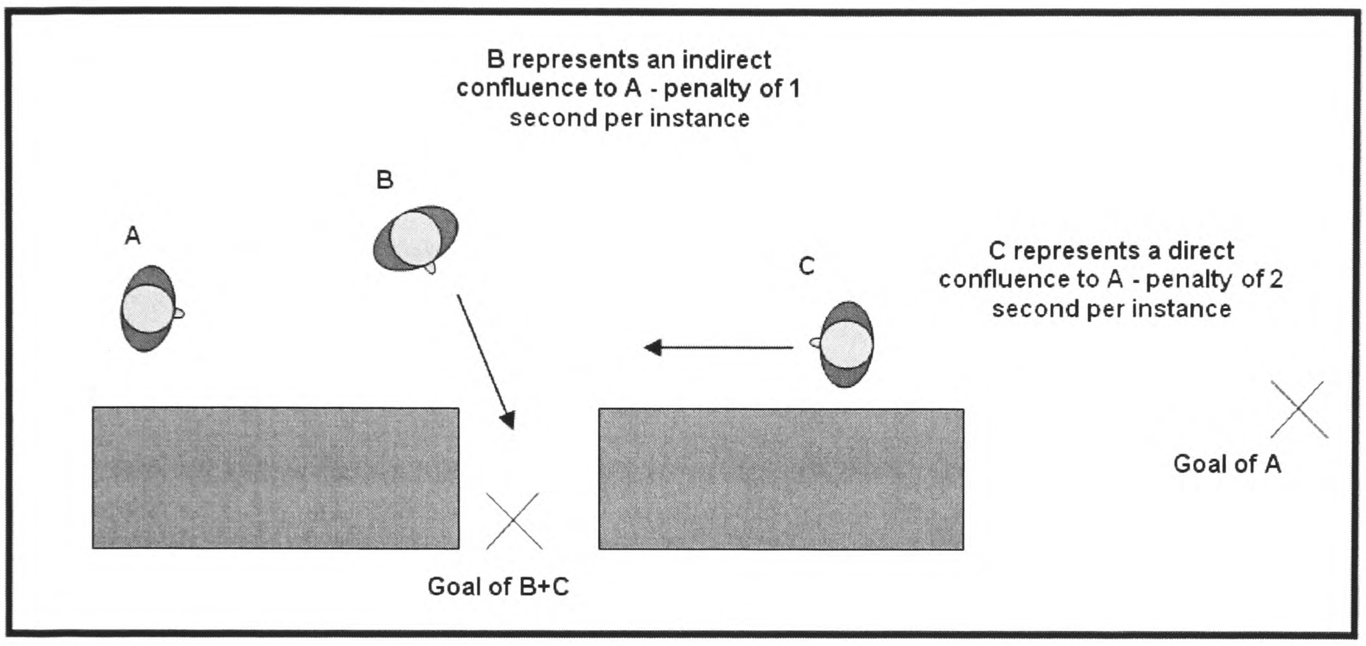


Figure 54: Examples of indirect and direct confluence

If the cabin crewmember suspects confluence then an appropriate penalty, determined according to the severity of the confluence, is added to the time required for the passenger to reach the exit, this is shown as Equation 17. A direct confluence is defined as one in which another passenger blocks the route and is moving directly opposite to the route of the passenger, i.e. Passenger C from passenger 'A's perspective in Figure 54. An indirect passenger is one that is not moving in direct opposition to the planned route but may still act as a hindrance, i.e. Passenger B from passenger 'A's perspective in Figure 54. Within the prototype every passenger on the proposed route (the route to T_{worst}) that is not using the alternative exit (T_{worst}) is assumed to be an indirect confluence. Direct confluences are determined via the direction of their movement. Finally, should the crew be unable to see the path to an exit then an amount of confluence is assumed for this portion of the route. The assumed level of confluence is determined using the ratio of confluence/space within the visible area for the route.

$$t'_{i,best} = \frac{d_{i,best}}{v_i} + t^c_{p,best} \qquad 17$$

t^c = the confluence penalty for passenger $_i$ en route to the alternative exit $_{best}$

t' = the revised travel time for passenger $_i$ en route to exit $_{best}$

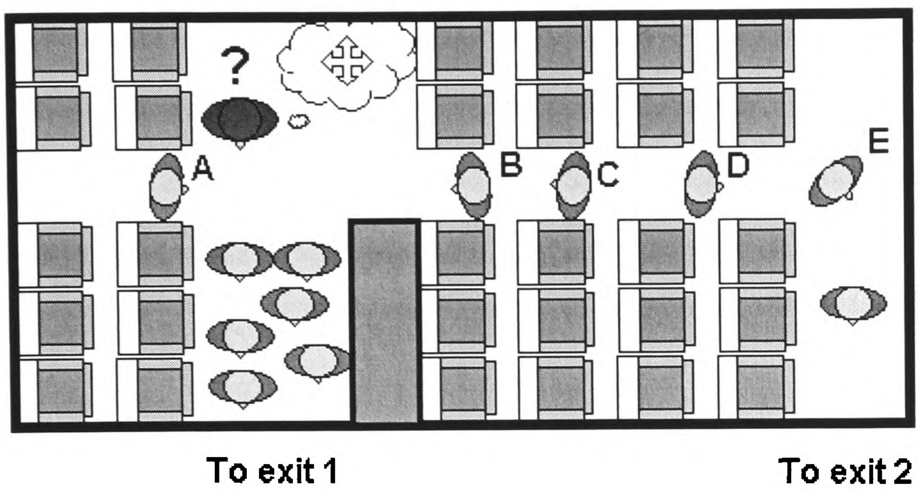


Figure 55: Hypothetical cabin section demonstrating a confluence situation

A hypothetical evacuation scenario is graphically illustrated in Figure 55. In this example the TDIS scheme is used. If the cabin crew were to determine whether there is merit in switching passenger A from the over utilised Exit 1 to the under utilised Exit 2, the likely confluence for the proposed route to Exit 2 would be factored into her decision making via an adjustment to the travel time assessment in Equation 17. In this example, the cabin crewmember would determine that there are five passengers on the route, two of whom (B and C) are moving in an opposite direction to the proposed route of passenger A. Given this the travel time to the exit is increased and thus the cabin crewmember would likely decide against redirecting passenger A. Whilst, it has not explicitly been stated within the model that crew should avoid redirecting passengers into an flow of passengers moving in the opposite direction, however this behaviour emerges from providing the crew with a mechanism of understanding the implications of flow patterns within the aircraft.

This example is extremely artificial as the order that the crew assesses passengers for redirection is determined by the time that it would take them to reach the alternative exit, thus presuming that they are visible and within effective communication range, the crew would consider redirecting passengers C and B before finally considering passenger A. The example is provided merely to illustrate how the simulated crew would factor confluence effects into egress route calculations.

The calculation of the time that it takes the passenger to reach the exit (Equation 4) utilises both dynamic and static information. The distance of the entire route to each of the exits is static information and should be known by the crew. However, the potential number of confluences en route must be obtained during the evacuation, this is dynamic information that must be collected. The two previously proposed methods, i.e. TDIS and LOSIS, are appropriate for crew redirection. An assumption of the model is that when using the LOSIS scheme the crewmember estimates the level of confluence in non-visible areas using a ratio of confluences/metre in the visible area.

Using this method an ordered list of eligible passengers for redirection is calculated. However, redirecting them may not yield any benefit as it may take them a long time to reach the alternative exit (T_{worst}). The crew must then assess their travel times against the size of the exit imbalance.

To do this a revised estimate of the flow time of the alternative estimate is first calculated adding one to the number of users (i.e. $p_{best} + 1$ in Equation 13). In addition it is necessary to calculate a revised clearance time for the exit from which the passenger has been donated. This involves subtracting one from the total number of users for the exit responsible for p_{worst} (i.e. $p_{worst} - 1$ in Equation 13

If the alternative exit is relatively free from passengers then it could be that the revised estimate of the finish time of the alternative exit is merely the time required for the redirected passenger to reach the exit. However, if the alternative exit is being utilised by numerous other passengers then the revised finish time may be a function of the number of passengers using the exit. It is necessary to determine which of these two factors is greatest. A simple estimate for the finish time of an alternative is calculated as the greater of either the time required for the total number of passengers to flow through the exits, i.e. Equation 13, or the time required for the redirected passenger to travel to the exit taking into account any confluence, i.e. Equation 17. Thus, the revised estimate of the finishing time of an alternative exit evacuating, presuming that the passenger is redirected, is calculated as Equation 18.

$$T''_{best} = Max\ (\ t'_{i,best}\ ,\ T'_{best}\ ) \qquad 18$$

T'' = the revised estimated finish time for the exit $_{best}$

If the revised estimate of the finish time for the alternative exit (T'') is less than the revised finish time of the donating exit, i.e. T'_{worst}, then there is merit in redirecting the passenger, see Equation 19.

$$if\ (\ T''_{best} < T'_{worst}\ ) \rightarrow Redirect \qquad 19$$

It may be that the cabin crewmember determines that there is no advantage to be gained from redirecting the passenger best placed for redirection to T_{worst}, i.e. the first passenger in the crew's ordered list of eligible passengers. Should the nearest passenger be found unsuitable then the cabin crewmember would not redirect anyone, but would continue to assess the situation in the hope that one passenger will offer a benefit in future. Presuming that a passenger is found that will alleviate the imbalance in the likely finish times of the exits, the cabin crewmember then performs a final check to make sure that bypassing the passenger would not lead to a period of exit inactivity at a local exit. It would be a waste of time to redirect the passenger if the path to the closest exit is free. In other words the cabin crewmember must ensure that a flow of passengers is maintained to closest exits, including the exit from which passengers are being taken and redirected. This is a logical necessity, as cabin crew would surely not redirect a passenger who is adjacent to an idle exit to another exit in the cabin section.

Thus the model should contain a final assessment of local conditions before issuing the command to a passenger. It could be argued that this assessment is made before any redirection is considered, i.e. the crew only consider redirection if local conditions are appropriate. Indeed this may well be the case. However, within a sequentially structured program, such as airEXODUS, an order has to be specified. From the perspective of computational load, it was better to have the crew assess local conditions only when a redirection was likely to be required. In terms of the development of this model, the argument is irrelevant as long as both checks are made prior to redirection being performed. Thus, the 'final' assessment has the crew assess conditions at the local exit prior to redirecting passengers. The judgment of local conditions is complex and varies according to the geometry of the structure and the exits that the crew is managing.

This check involves the cabin crewmember scanning the paths of passengers within their redirection zone (as determined via the visual and later communication algorithms) to the nearest exit from the crewmembers location. A general check that passengers' paths are relatively free from others, i.e. has a 1 passenger/metre density across the route, is first performed. If the density is below 1 passenger/metre the crewmember deems that the flow to their local exit is thinning and chooses to redirect the passenger to the closest exit instead. In addition, two specific flow patterns within the model also alert the crew that redirection away from the nearest exits is ill advised. The first is only used when the crew is adjacent to an active Type-III exit, i.e. within 2 metres of the exit. In this situation the crew will only redirect a passenger away from the exit if the through seating passageway that leads to the exit is completely full of other passengers. In other words if the seating is not completely full then the crew will reject redirection and determine that the flow to the local exit is thinning (see Figure 61(a)). The second flow pattern is used when redirecting passengers away from floor level exits only. Within the prototype this is achieved by having the crew notice when a sizable gap develops between the passengers and the queue to the local exit (see Figure 61(b)). The size of the gap is arbitrarily set to approximately 1.5 metres.

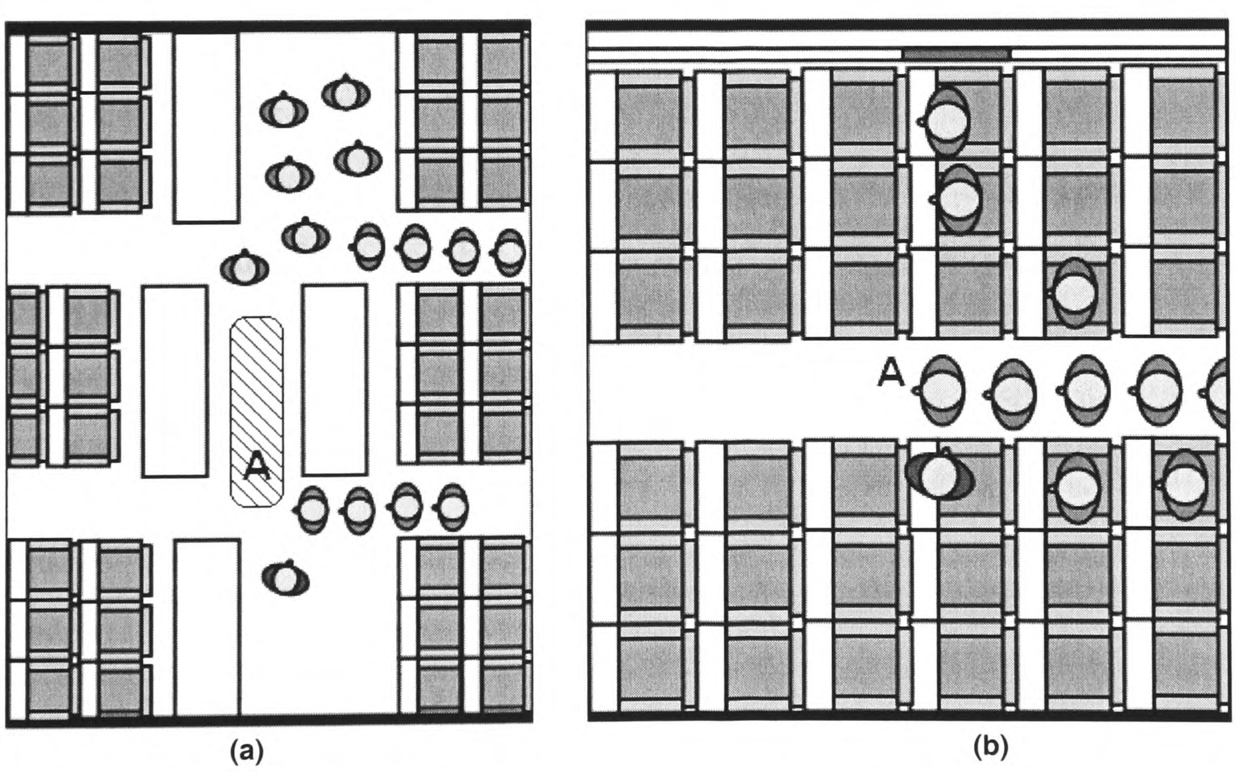


Figure 56: Two examples of conditions that would trigger a local exit override within the model, (a) denoates a break in the flow to the local exit (marked as area A) whereas b) demonstrates a break in flow at a type three exit.

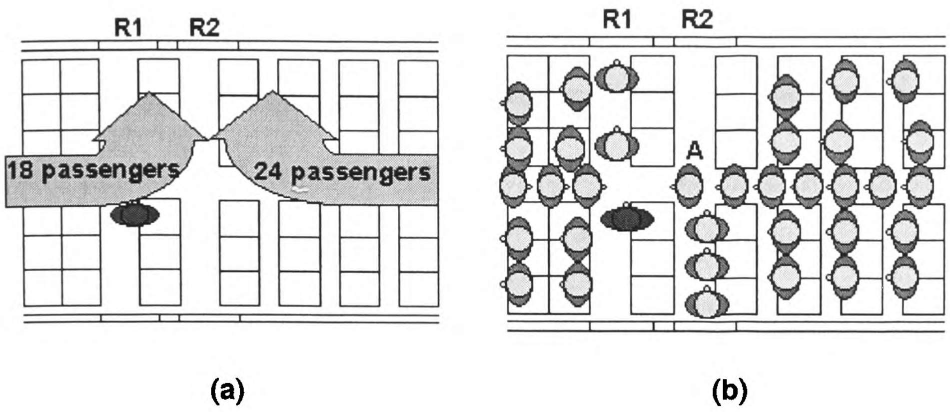


Figure 57: A hypothetical cabin section which would require bypass (a), and an example of the cabin section during an evacuation – passenger A would not be bypassed as a closer exit is free

In this manner a period of inactive flow the crew's local exit overrides any redirection to more distant exits. Thus, a flow of passengers is achieved between the exit that requires additional passengers and the exit from which passengers are being taken.

Figure 57, represents a hypothetical cabin section in which 42 passengers seats are located. The cabin section contains two pairs of Type-III over-wing exits, of which only the right side are active. Figure 57 (b) shows the cabin section during an evacuation. It can be seen that 13 passengers are located forward of the R1 exit and 22 are located rear of R2. A cabin crewmember is positioned adjacent to the Type-III exit and is attempting to balance the number of passengers using each exit.

From Figure 57 (b) it is apparent that there is a need for some of the passengers that are likely to use the R2 exit to be bypassed towards the R1 exit. However, bypassing passenger A in Figure 57(b) would be counter productive, as the passenger has an unobstructed route to a closer exit (R2). Whilst bypass is necessary, choosing to bypass passenger A would not be advisable, as this would increase the period of inactivity at the R2 exit. In such an event the cabin crewmember would redirect passenger A towards the relatively inactive exit R2. Indeed the rules of the model would allow the crew to bypass a passenger only when the seats that lead to the Type-III exit are completely full of passengers.

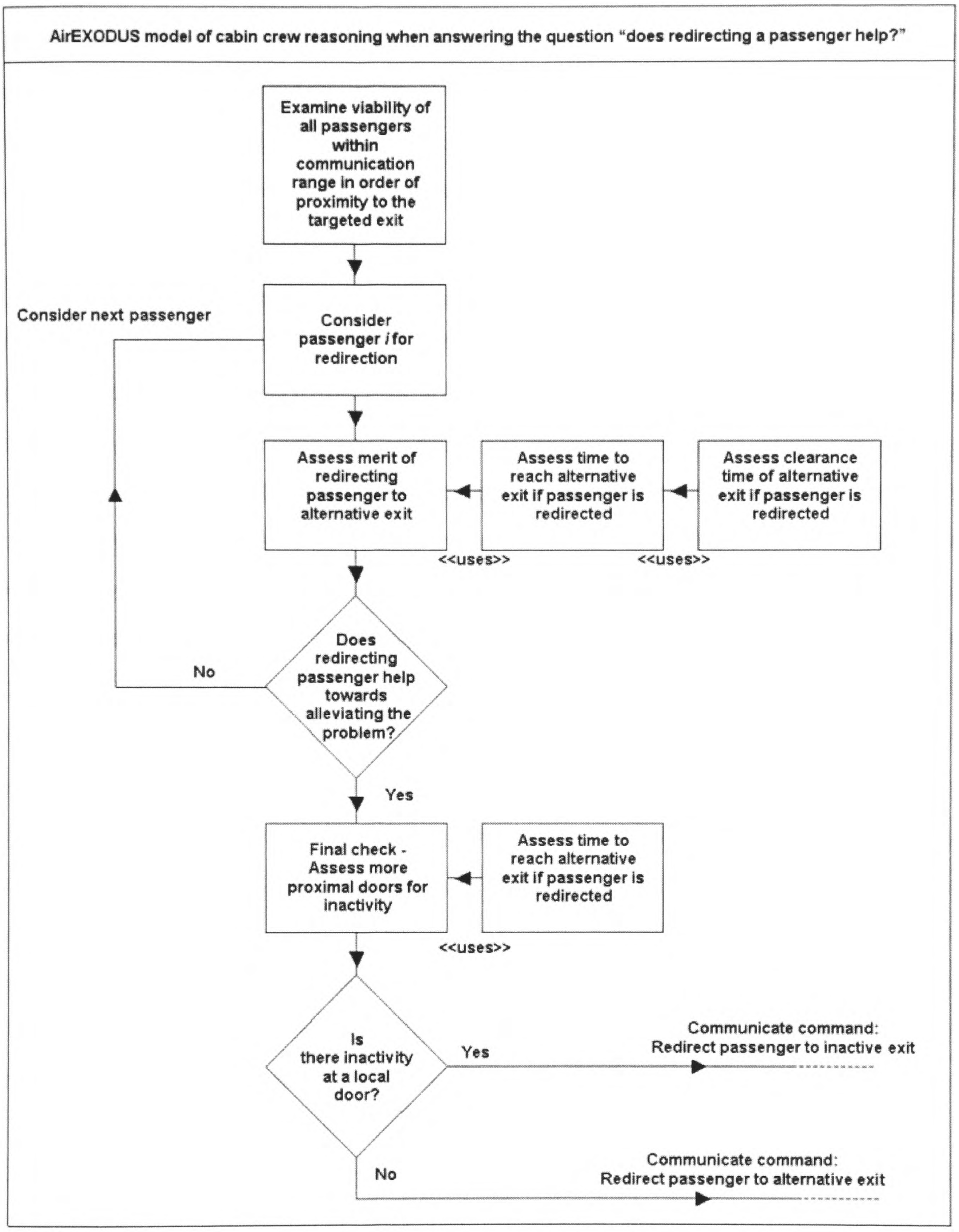


Figure 58: Flow chart of the airEXODUS implementation of cabin crew directed bypass or redirection

Finally, the decision was taken that passengers may be redirected multiple times as this type of behaviour has been observed in several actual accidents (see the Manchester evacuation in 1998 and Dallas Fort-worth in 1993, Section 5.4.6.4 and Section 5.4.5.1). Indeed, similar situations could arise within the model when using the LOSIS visibility method as crew with different levels of visibility may each determine different 'best options' for the aircraft as a whole. In this event the most recent adopted command is followed by the passenger.

This completes the portion of the prototype model that detects the need for redirection and selects an appropriate passenger. A complete sequence of events described in this section are summarised as a flow chart in Figure 58. Presuming that the cabin crewmember wishes to redirect a passenger the next stage is for the crewmember to communicate the command to the passenger.

A model to represent crew to passenger communication

Once a cabin crewmember has decided to redirect a particular passenger they must communicate an instruction/command to the passenger. As mentioned previously cabin crewmembers have the ability to communicate their instructions to passengers through a number of different methods. Typically they are through gestures, verbal commands, or physical encouragement. In reality methods of communication would be numerous perhaps involving shouting and/or waving of arms. Within the prototype model communication is categorized as being either *verbal* or *physical*. Within the prototype model two concentric circles are defined around the crewmember that represent the range of effectiveness for each type of communication. One represents the range within which a cabin crewmember may physically handle or touch passengers. The second radius represents the range within which a cabin crewmember is able to communicate to passengers through voice and/or gestures. Within the model touch range is uniformly applied to all crew and is fixed at 1 metre, i.e. arms length, whereas the voice/gesture range varies according to the abilities of the crew and the conditions within the cabin. Situations in which the crewmember leaves the duty station to redirect passengers is the subject of future work.

Within the prototype model only passengers that are located within the cabin crewmember's touch range, such as passenger A in Figure 59, may be physically handled by the cabin crewmember. Those passengers outside the touch range cannot be physically communicated with. However these passengers may be communicated with through verbal communication or gestures. In other words, those passengers that are located outside of touch range, such as passenger B in Figure 59 but are located within the voice/gesture range may be communicated with through verbal communication or gestures. Passengers that are located outside of both touch and voice/gesture range, such as passenger C in Figure 59, may not be able to receive any communications.

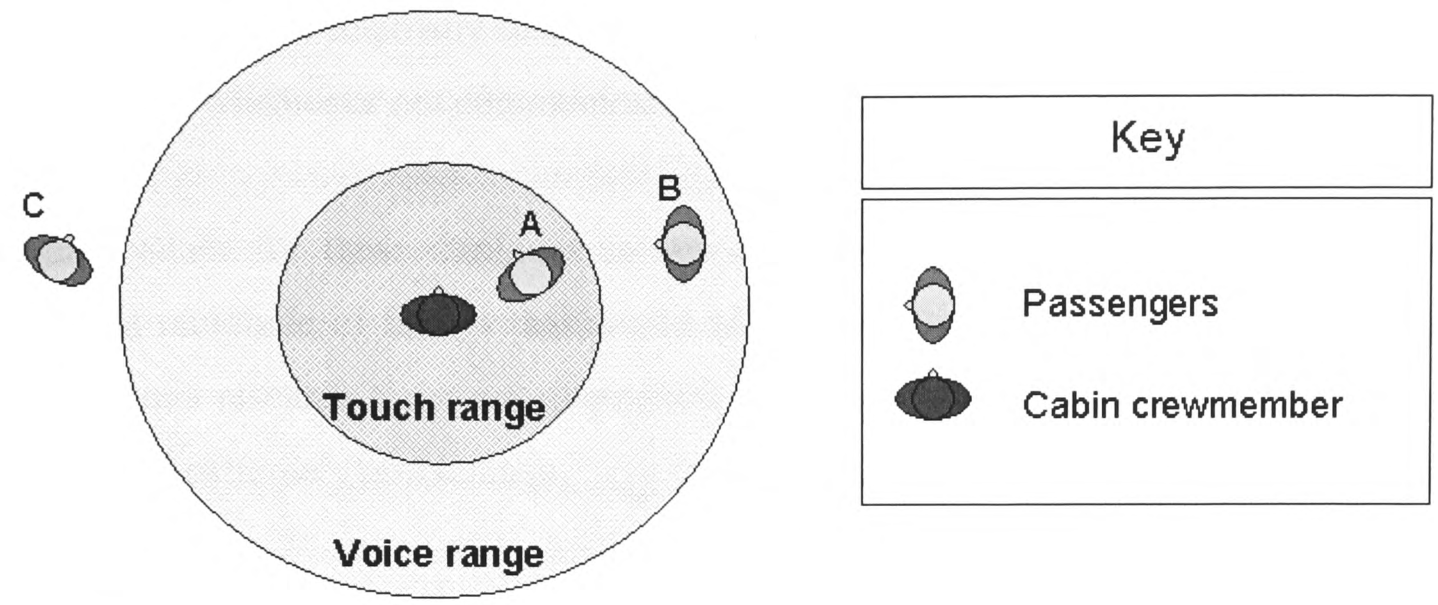


Figure 59: Example of communication ranges. Passenger A is within ***touch range*** passenger B is within ***voice/gesture range*** and passenger C is beyond the range of this communication for this cabin crewmember.

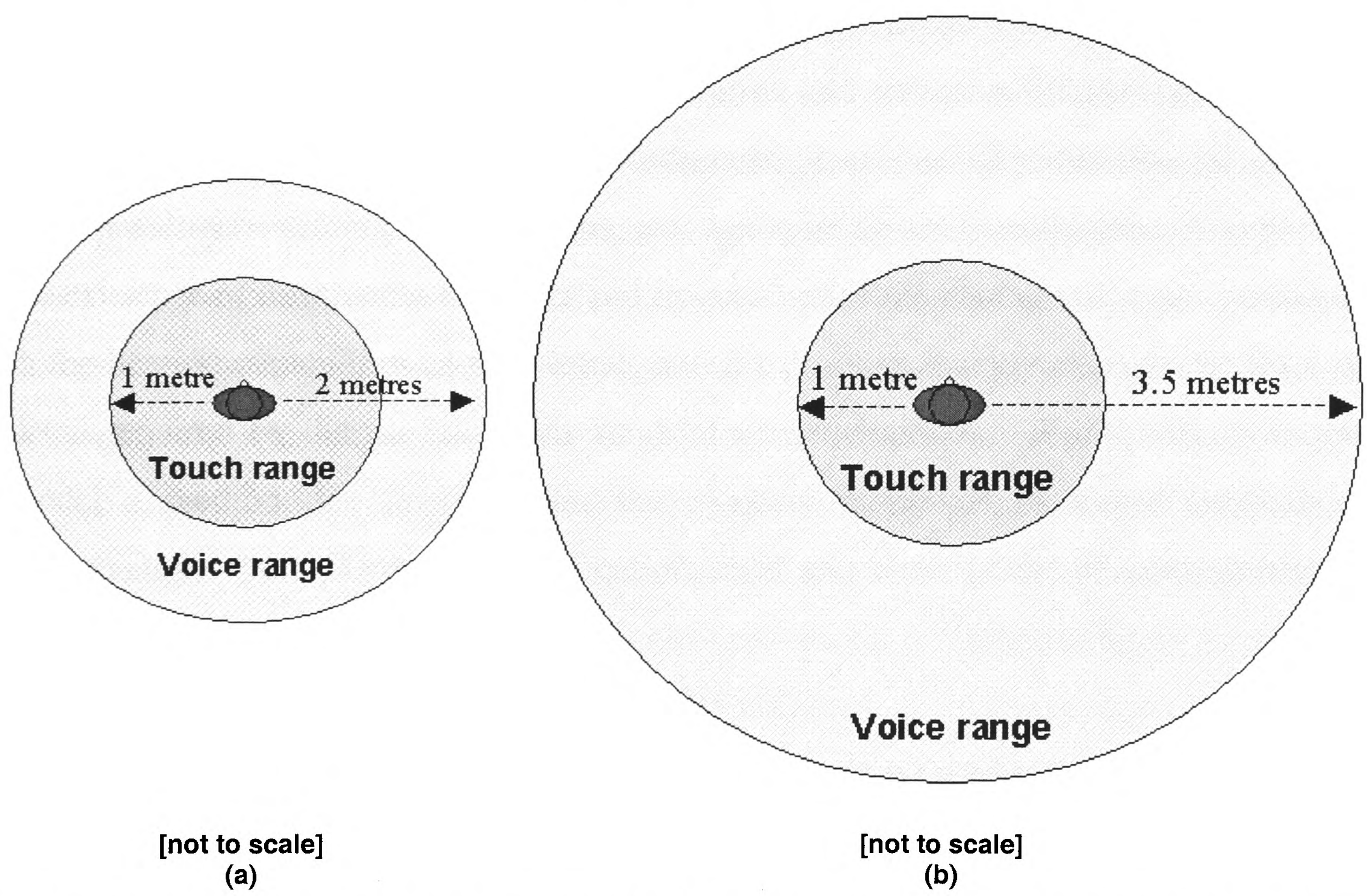


Figure 60: Two different cabin crewmembers with different levels of communication effectiveness, (a) a cabin crewmember with a relatively low level of voice/gesture effectiveness and (b) a cabin crewmember with a relatively high level of voice/gesture effectiveness

In reality when considering redirecting passengers the crew may only consider passengers that they consider susceptible to their influence. Whilst in some circumstances it may be beneficial for them to redirect passengers that are 10, 20 or 30 metres away from them, they may not always choose to do so. For example in very densely packed noisy conditions the crew may choose not to communicate with passengers that are relatively distant. In essence the crew have some mechanism for determining whether or not communication attempt is worth attempting.

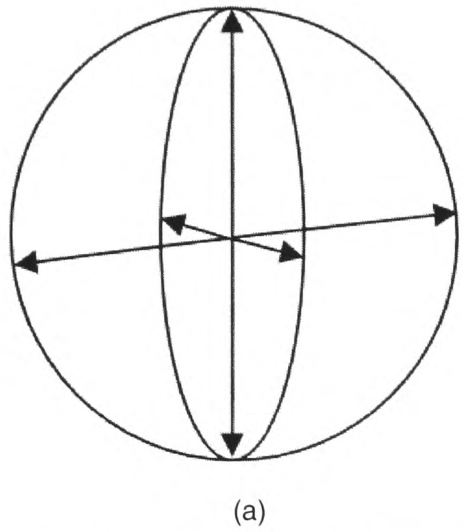
Setting values for these attributes for use within the model is extremely difficult. Indeed a multitude of factors that would which prove extremely difficult to quantify from current research make a mathematical calculation of the effective vocal range for cabin crew extremely problematic.

In reality absorption effects from boundaries, i.e. walls and furnishings, impact upon such a range and are dependant upon the properties of the boundaries and types of furnishings. This is compounded further by atmospheric factors that serve to scatter sound. These factors vary according to air temperature, density, the presence of smoke particulates, etc. In addition, sound reverberation and reflection effects would need to be considered: within the enclosed environment of an aircraft cabin, the location of other passengers, seating, stowage bins, etc, would influence these factors. Add to this, the existence of differences in power and frequencies of the human voice and variations in the hearing capabilities of individuals and the problem quickly exceeds the level of detail required by the model at this stage of its development. Within this prototype model a method that approximates the physical properties of sound attenuation, observaations from 90-second certification trials and descriptions of communication from accident reports is developed.

To determine an overall trend for sound attenuation, we assume that shouting has an Intensity (I) of 1 watts/metre^2 when 20cms from the source and that background noise, i.e. conversation, has a constant Intensity (I) of $6*10^{-6}$ watts/metre^2 at every distance from the source [165]. We also assume no reflection, absorption or boundary effects. The sound waves propagate spherically (see Figure 61(a)) from the source. With these assumptions, the power of the signal is determined according to:

$$\textbf{Sound level in dB at range } r = 10 \log[\,(1/4\pi r^2)/I_0\,] \qquad 20$$

where $I_0 = 1 \times 10^{-12}$ (*the intensity of a pin dropping (watts/metre^2)*)
$I = 1$ (*initial intensity (watts/metre^2)*)
$4\pi r^2$ = *the surface area of a sphere with radius r*
r = *the range*



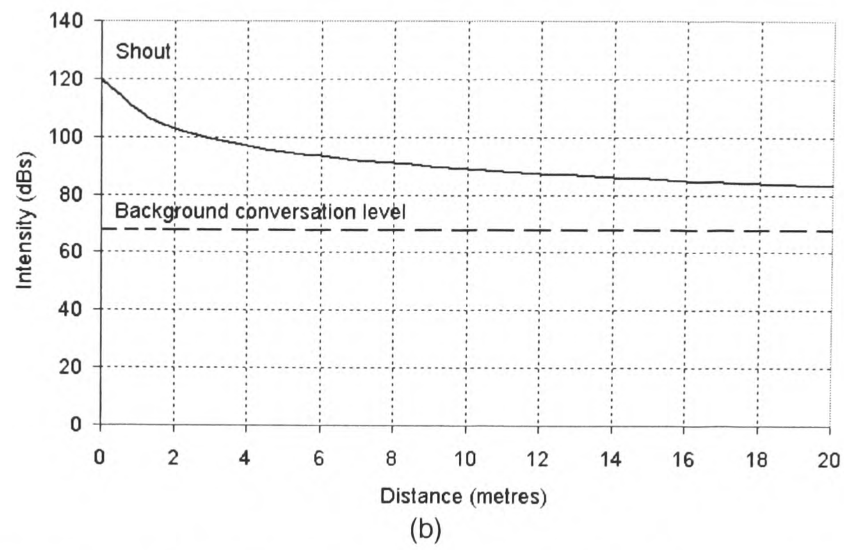


Figure 61: an example of (a) spherical propogation without boundaries, and (b) a simplistic example of sound attenuation as a function of distance

Using Equation 20 [165], a sound level of 120dBs is calculated for shouting when 20cms from the source (see Figure 61(b)) while background noise from conversation has a uniform sound level of 68dBs. The power of the shout diminishes from 120dBs to approximately 97dBs at 4 metres. Indeed, the general physical trend for sound attenuation is a quick initial decay followed by a slow decline over greater distances.

Qualitatively, video footage from 90-second certification trials shows crew communicating with passengers some distance away. However, in most circumstances communication from crew to passengers at the other end of cabin sections are rare. In most instances the crewmember would have to move some distance into the cabin section in order for the communication to become effective. A further observation from 90-second certification trials is that crew communications over large distances are less frequent during the early portion of evacuations when the cabin is densely populated. During the early portion of evacuations the crew tend to communicate with passengers within close proximity to themselves. This may result from the high number of passengers that are present within the cabin making communication over large distances extremely difficult. As the cabin begins to empty crew typically attempt to communicate to more distant passengers. During the final 10-20 seconds of certification trials crew are frequently witnessed shouting at individual passengers over relatively large distances (approximately 10 metres).

Using the trends of sound attenuation (see Figure 61(b)) as a guide, a functional relationship is proposed for use within the prototype model. The functional relationship links the probability of crew communicative effectiveness within the passenger density in the cabin (see Figure 62). Whilst there is insufficient data to perform quantitative verification of the proposed relations, qualitative aspects of the relation is supported through video footage of 90-second certification trials and the general properties of sound attenuation (see Figure 61(b)). For example, from the sound attenuation curve in Figure 61(b) it can be seen that the difference between the intensities (dB) of the shout and background communication reduces by 50% within the first 6 metres. The low density effectiveness curve constructed for use within the model shares this trend (see Figure 62).

However, after 6 metres the reduction in the mathematical curve (see Figure 61(b)) is less pronounced and decreases slowly with the two intensities converging at a distance of 100 metres. This trend is unsupported from analysis of video footage of 90-second certification trials, in which instances of crew communicating effectively beyond cabin partitions usually spaced at intervals of approximately 20 metres (60-feet) have not been witnessed. Consequently within the model and in low density conditions, communication effectiveness beyond 6 metres decreases at a more quick rate than the mathematical curve (see Figure 62), reaching a near zero value at 20 metres (60-feet).

As mentioned previously, qualitatively evidence from 90-second trials suggests that communication is less effective during medium and high passenger densities. Within the prototype model two more hypothetical curves (see Figure 62) are provided to represent reduced communication effectiveness in medium and high density conditions. These curves share the general trends of the low density curves however serve to reduce communication effectiveness in medium and high density conditions.

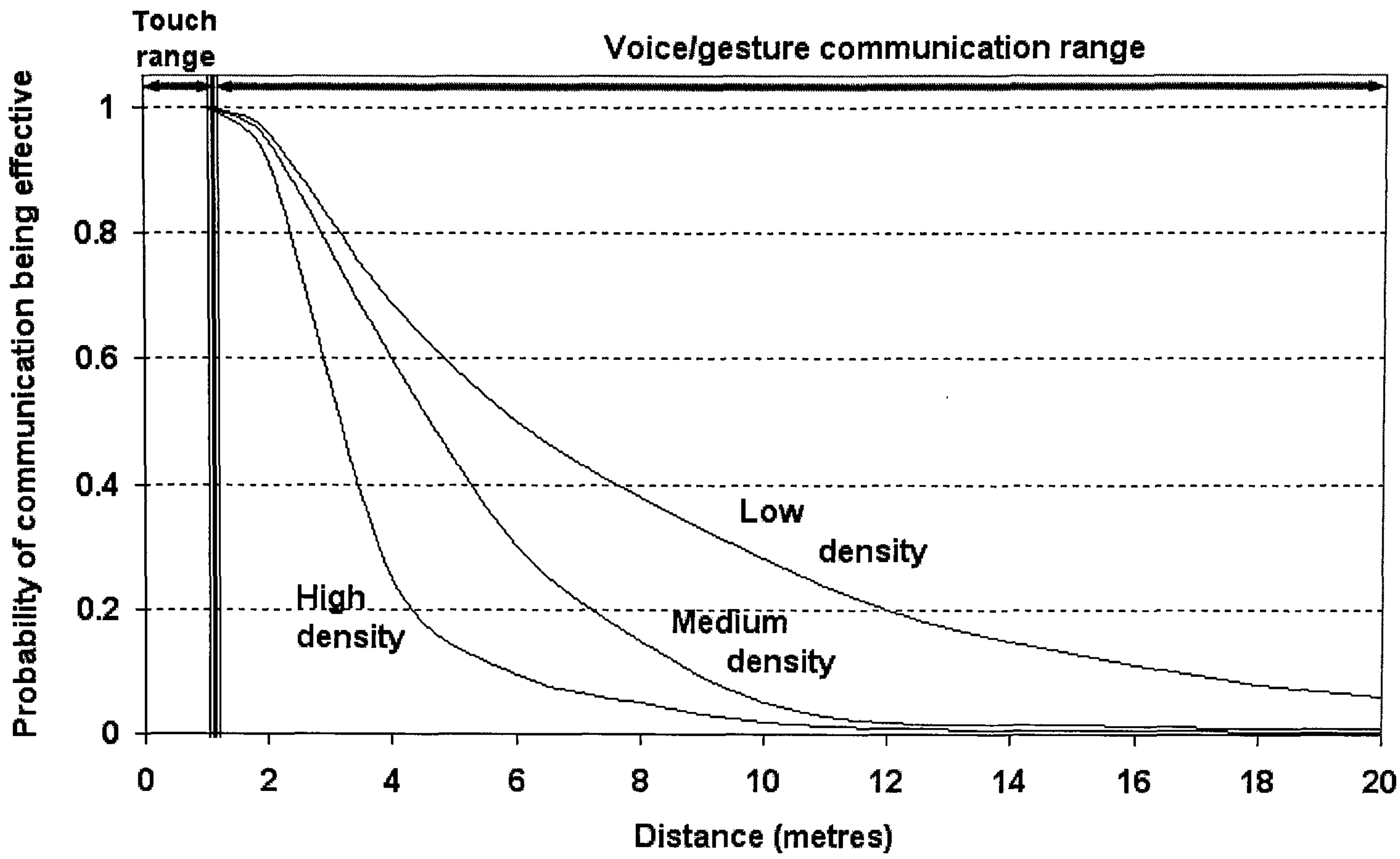


Figure 62: Hypothetical functions to represent cabin crew communication effectiveness

Within the prototype model the density will be sampled within a 10 metre radius of the crew, i.e. the immediate vicinity of the crew. Low density is arbitrarily set as being <0.1 passengers/metre^2, high density as greater than 0.4 passengers/metre and medium density any where in-between high and low. Reflecting the features of sound attenuation the hypothetical curves have long tails that represent very low probabilities of communication being effective. Based on these two composite linear functions were defined for each density (see Figure 63) and provide a reasonable fit to the hypothetical curve (see Figure 62).

Within the prototype model the communication range is set to the distance at which communication is effective which is randomly determined using the curves previously described (see Figure 63). As the density within the cabin is subject to change a new calculation is made each time a crewmember attempts a communication.

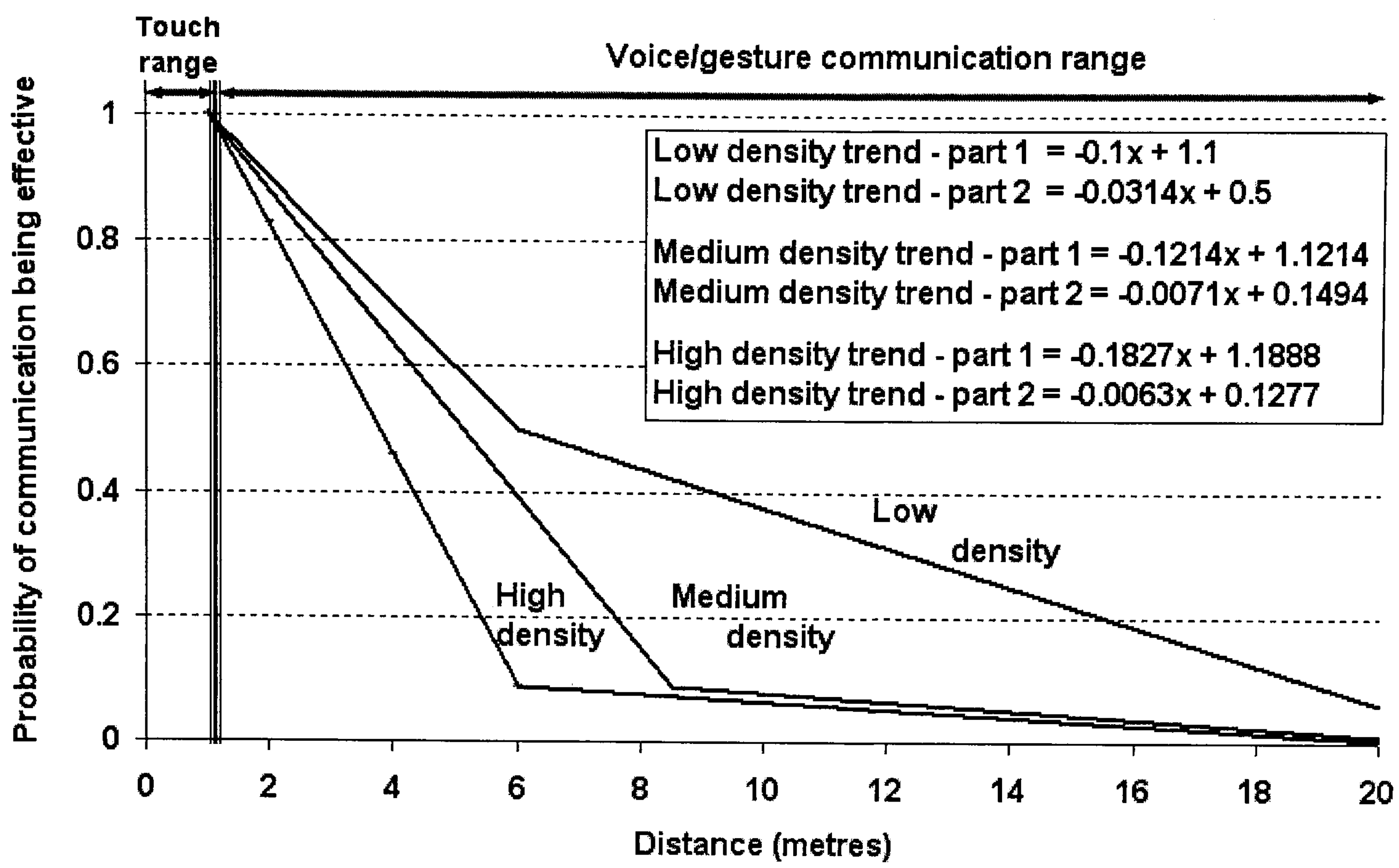


Figure 63: Linear function to represent cabin crew communication effectiveness

A finding of the investigation into human behaviour in real emergency evacuations in Chapter 5 was that communication is likely to be more difficult in smoke environments (see Section 5.4.1). This is due primarily to the effects of irritant gas on the throat and lungs, although other factors such as increased scatter from smoke particulate and/or increased background noise from fire fighting activities may also impact upon the effective range of the cabin crew. When considering communication in smoke filled environments it is apparent that another set of complex interacting factors exist.

Again there is insufficient data to quantitatively define a relationship between communication effectiveness in smoke as compared with clear air. Thus some simplistic approximations are made and used within the prototype model. Again these are based on the analysis of past aircraft accidents in which it was apparent that communication was more difficult in smoke filled environments. This investigation indicated that some reduction is clearly necessary for the model to be realistic. The value of such a reduction is likely a function of the factors mentioned above and is extremely difficult to define and generalise. It is therefore suggested that to model an 'effect' the effectiveness threshold probabilities are reduced by approximately half whilst maintaining the general trends of those in clear air.

It is recognised that the adopted approach to communication is somewhat crude. However, the models are based on understanding of the physical processes involved and qualitative understanding of the resulting behaviours. The models that have been proposed allow a broad approximation to the observations of communication in from 90-second certification trials. Whilst the values generated by the model would undoubtedly vary in reality, the broad trends captured within the model (i.e. smoke reductions, attenuation over distance, etc.) are considered a reasonable correlation to reality being based to some degree on observation and the physical properties of sound attenuation. Finally, the inclusion of this representation of communication will allow additional scenarios involving communication to be modelled, which as mentioned previously broadly represent the trends found in aircraft evacuations and the physical properties of the process.

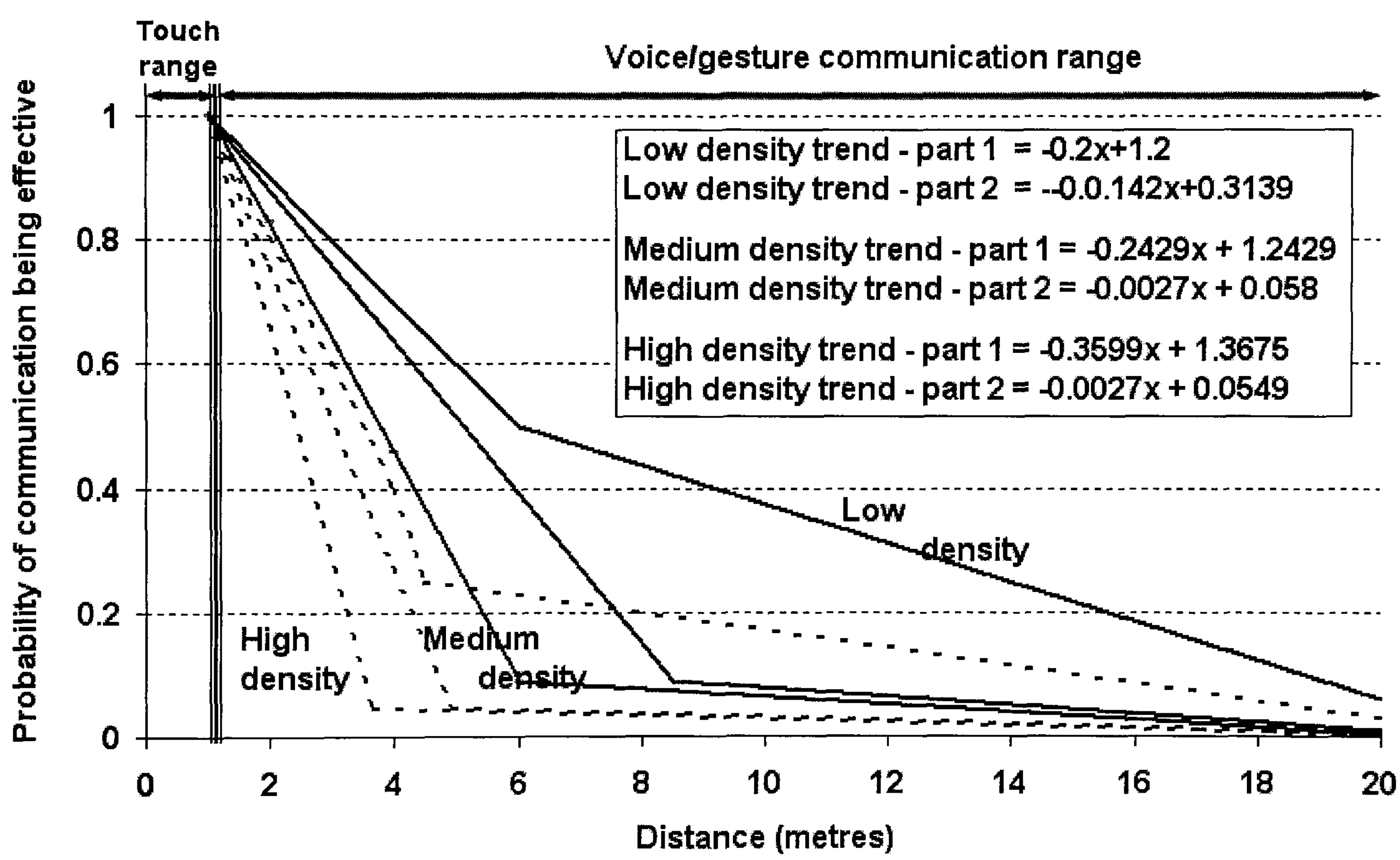


Figure 64: Hypothetical functions to represent cabin crew communication effectiveness in smoke

Within the prototype model the crew will make judgements on whether it is worth attempting to communicate over certain distances. Where the probability of their being successful is too low, they will disregard the option and instead focus on closer and more viable communication options. This reflects the observed behaviour from 90-second certification trials in which the crew are unlikely to attempt to communicate with very distant passengers during the early stages of the evacuation when the cabin is densely populated. Furthermore, as the cabin begins to empty the crew will perceive communication becoming easier and more effective and thus attempt to communicate over larger distances. As the cabin completely empties the crew may attempt to communicate over relatively large distances.

Another aspect of the crew communication process involves whether the passenger will obey or disregard the command of the crew. In reality factors such as whether the passenger agrees with the crew, whether other passengers have obeyed the crew, whether the crew is redirecting you towards what you precieve to be a dangerous route, whether you have the stamina to undertake their instructions, etc., would all influence decision of the passenger to accept or reject the command of the crew. Given the lack of research in this area it is extremely difficult to model this behaviour taking into account all of these factors. However a representation is required within the prototype model.

Within this prototype a simplistic functional relationship between the passengers Drive and the Assertiveness of the crew is adopted. In essence this approach models a fundamental level of agreeability by the passenger to the commands of the crew which is affected by the assertiveness of the cabin crew. In a later section of this work a method for having passengers' agreeability affected by severity of the scenario is proposed.

Within the prototype model an assertiveness attribute is used to represent the forcefulness of the crew when communicating. The attribute is assigned values between 0-15, in which 2 would represents low and 15 high assertiveness. Video footage of 90-second certification trials demonstrates individual variations in the assertiveness levels of cabin crew. From example, some crew are averse to forcefully pushing passengers towards a desired location and choose to communicate verbally through the evacuation, whereas others forcefully grab passengers and hurl them in the desired directions. Thus, within the prototype model an assertiveness level can be assigned to each crew member that will influence their ability to enforce their redirection commands onto passengers.

From video evidence of 90-second certification trials it was apparent that when a cabin crewmember can actually physically handle a passenger their instructions tend to carry greater force than a verbal instruction or a wave of an arm. In other words, pushing a passenger towards a desired location delivers the instruction with greater power and force than merely asking them to move or gesturing. In other words the verbal command conveys less urgency than physically handling passengers.

To represent this within the model when communicating with passengers via verbal or gesture communication an (arbitrary 2 point) penalty is applied to represent the relative difficulty of communicating via this method. No such penalty is applied when communicating with passengers that are within touch range. The values can be changed should data indicate more appropriate settings. The effect of the penalty is that passengers are less likely to do as instructed when communicated with verbally than when communicated with by physical means.

As mentioned previously passengers' response is simplistically represented using the Drive attribute which is assigned to all passengers within the model. The Drive attribute is thought to be appropriate as it characterises the passengers' competitiveness. Within the model the Drive attribute is assigned values from 1 (low drive) to 15 (high drive) according to the age and gender of the passengers. There is some evidence to support the belief that young males generally have the highest drive while older females tend to have the lowest drive. This is suggested from competitive evacuation trials involving financial payments to evacuees who are amongst the first few to successfully evacuate [127,122]. A similar relationship may exist with respect to passenger subservience to crew commands. For example, a frail elderly female may be less able to resist a forceful push from a cabin crewmember than a young fit male.

Within the prototype model the probability of the passenger doing as instructed is represented via a linear function of the assertiveness of the cabin crew and the receptiveness of the passenger to their commands (see Figure 40). The outcome of the command is determined by the person with the highest value, i.e. passenger Drive versus crew Assertiveness. For instance, a passive and unassertive cabin crew (Assertiveness = 3) may not be able to dissuade an elderly but stubborn passenger from disobeying their wishes (Drive = 5). Thus, within the prototype model passengers with high Drive will be more likely to ignore the commands of cabin crewmembers than those passengers that have low Drive. Likewise a relatively timid cabin crewmember

(Assertiveness = 3) may be able to influence those passengers that are subservient (Drive = 2). However, the same cabin crewmember may have difficulty in influencing the behaviour of insubordinate passenger (i.e. Drive > 3).

Table 39: The look-up table for passengers obeying the command of cabin crew

		Passenger drive		
		Low (1-5)	Medium (6-10)	High (11-15)
Cabin crewmember assertiveness	Low (1-5)	Obey	Ignore	Ignore
	Medium (6-10)	Obey	Obey	Ignore
	High (10-15)	Obey	Obey	Obey

A finding of Chapter 4 was that in 90-second certification trials the crew are highly effective at controlling passengers. Indeed it is relatively uncommon to observe disobedience when examining certification trial video footage. Thus it is recommended that the communication assertiveness of crew is set to maximum levels for 90-second certification trials. In this behavioural regime ALL passengers would be totally subservient to the commands of crew.

The final element of the prototype 90-second certification trial redirection model concerns the temporal component to communication. When a crewmember issues a verbal command, the act of issuing the command requires an amount of time – some time is utilised in forming the words, waving arms or handling the passenger. To represent this within the model the act of communicating a command to an individual passenger requires an amount of time. At present the time penalty attached to communication is arbitrarily set to half a second. Whilst the actual value of the number is completely arbitrary, it is clearly necessary to have some representation of what is clearly an important physical aspect to communication.

A method of representing imperfect crew performance

At this stage the simulated crew redirection model would lead the crew to always make a near perfect assessment of redirection based on the information available to them. However in reality, humans are fallible and are capable of making poor decisions. Thus, at present this model simulates a somewhat artificial situation. In order to better reflect reality the model requires a mechanism of representing the fallibility of crew when making rapid and complex decisions.

In reality numerous fallibilities are witnessed in evacuations. For example, crew may redirect passengers to exits that are not useable (see Section 5.4) and/or may determine that no available exits exist for redirection. Whilst important, at this stage of the model development fallibility is limited to the confines of the proposed model. The proposed method of crew fallibility introduces inaccuracy into the crewmember assessment of the clearance time of the exits (Equation 13) and the movement speeds of passengers in reaching alternative exits (Equation 16). This is randomly generated within a user specified range and serves to increase or decrease to the estimated flow rate of the exits (f_i), the movement speeds of the passengers (v_i) and the distance that the passengers has to travel to the exits (d_i). This scheme represents a slight misjudgement of the time required to evacuate passengers through the exit and would affect the crewmember's ability to determine whether redirection is beneficial.

The level of error should vary according to the proximity of the exit to the crew. For simplicity exits have been categorised as being either local, i.e. closest to the crew, or distant, i.e. all other exits. The user is able to specify different percentage errors to local and more distant exits. If supplied, these error bounds affect the entire crew complement.

6.1.1.2 Summary

The model proposed thus far encompasses the main aspects of the bypass procedure, namely the crew's movement to the redirection station, their dynamic assessments of the optimality of exit usage, a method of determining if redirecting a passenger would improve evacuation optimality and finally a method of communicating a redirection instruction to the passenger. However, the model that has been described has been developed thus far is appropriate ONLY to 90-second certification trials. The next sections extend the model to more realistic emergency evacuation situations.

6.1.2 Extending the model to simulate redirection during real emergency evacuations

In 90-second certification trials the general mode of behaviour is that passengers do as instructed by cabin crew. However, from the analysis of real emergency evacuations it was apparent that two forms of redirection operate in tandem as in real emergency evacuations passengers are actively seeking their own solution to the evacuation problem. Their solution involves an attempt to minimise their personal evacuation time. Thus, when modelling real emergency evacuations an additional model has been developed to represent passenger exit decision-making. Furthermore, some additional features are required to augment the crew redirection models. This section addresses these issues and describes the development of a model for representing passenger exit choice and crew redirection in actual emergency evacuation scenarios.

Before continuing it is necessary to reiterate the key findings of the data analysis. From a behaviour perspective evacuation scenarios can be broadly grouped as being those that involve some form of either, non-fire or external fire (referred to as non-fire scenarios), or burn-through scenarios or internal fire (referred to as fire scenarios).

Firstly, a model for simulating passenger exit choice during non-fire and external fires is presented and adaptations to the 90-second crew redirection model made. Building on this the model is further extended to encompass passenger and crew exit choice decision-making in burn through scenarios.

6.1.2.1 A model for simulating crew and passenger exit choice during non-fire

In order to represent crew and passenger exit choice, it was necessary to construct a model that was able to simulate passenger exit choice based on the analysis of the AASK database [6,7,102,103]. Having developed a passenger exit choice model, the 90-second certification trial cabin crew redirection model is extended. Finally, a scheme in which both of these models can operate in tandem is proposed.

A model of passenger exit choice

Based on the analysis of the AASK database, it was apparent that the rationale for the passenger exit choice model should be that each passenger attempts to choose an exit that offers the fastest evacuation time for them as individuals rather than for the evacuation of the aircraft as a whole. When considering their options passenger would use their own knowledge of the exit locations onboard the aircraft and the nature of the evolving evacuation scenario to calculate which exit is the best for them personally. In essence the passenger is performing their own flow rate calculation based on their understanding of their environment and the number of potential competitors for each of the exits. However, unlike the crew, the passengers' calculation is based on only tentative knowledge of the characteristics of the aircrafts' exits and involves them minimising their personal evacuation time.

This can be modelled via having each passenger estimate their own personal evacuation time if they were to use each exit. This calculation is presented as Equation 21.

$$T_{p,i} = pa_{p,i} f_{p,i} \qquad 21$$

i = the exits that are considered to redirect towards, i.e. R1, L1, R2....

p = the passenger under consideration

$T_{p,i}$ = Time estimate for passenger $_p$ using exit $_i$

$Pa_{p,i}$ = the number of passengers likely to reach the exit ahead of passenger $_p$ when using exit $_i$

$f_{p,i}$ = an estimate of passenger $_p$ for amount of time required to evacuate a single passenger through an the exit $_i$

In reality when determining a finishing time for an exit a passenger would only be interested in other passengers that could potentially reach the exit before them. Thus within the model the number of passengers ahead of passenger p when considering exit i is simply the number of passengers that are closer to the exit being considered. Within the model this calculation can be achieved via having the passenger use his distance from the exit as a radius within which other passengers are considered. Of interest to the passenger are only other 'viable' passengers who may use the exit under consideration. Within this prototype 'viable passengers' are defined as those that are located within aisles, vestibules and in the case of through seating exit passage ways, i.e. seating adjacent to Type-III exits. Passengers that are unbuckling seat belts are excluded from this judgement.

As an example Figure 65(a) shows a passenger who is considering the number of users of both exit 1 and exit 2 (seats, aisles, etc. have been excluded for simplicity). In determining this, the simulated passenger notes his distance from each exit (see Figure 65(b)) and extends a hypothetical catchment area using the distance from each exit as the radius. The simulated passenger then counts the number of passengers that are using each exit within each catchment area (see Figure 65(c)). The number of passengers for each exit i forms the $pa_{p,i}$ estimate used in Equation 21. A scheme for limiting his information according to the visual accessibility of the structure and environmental conditions is presented in later sections.

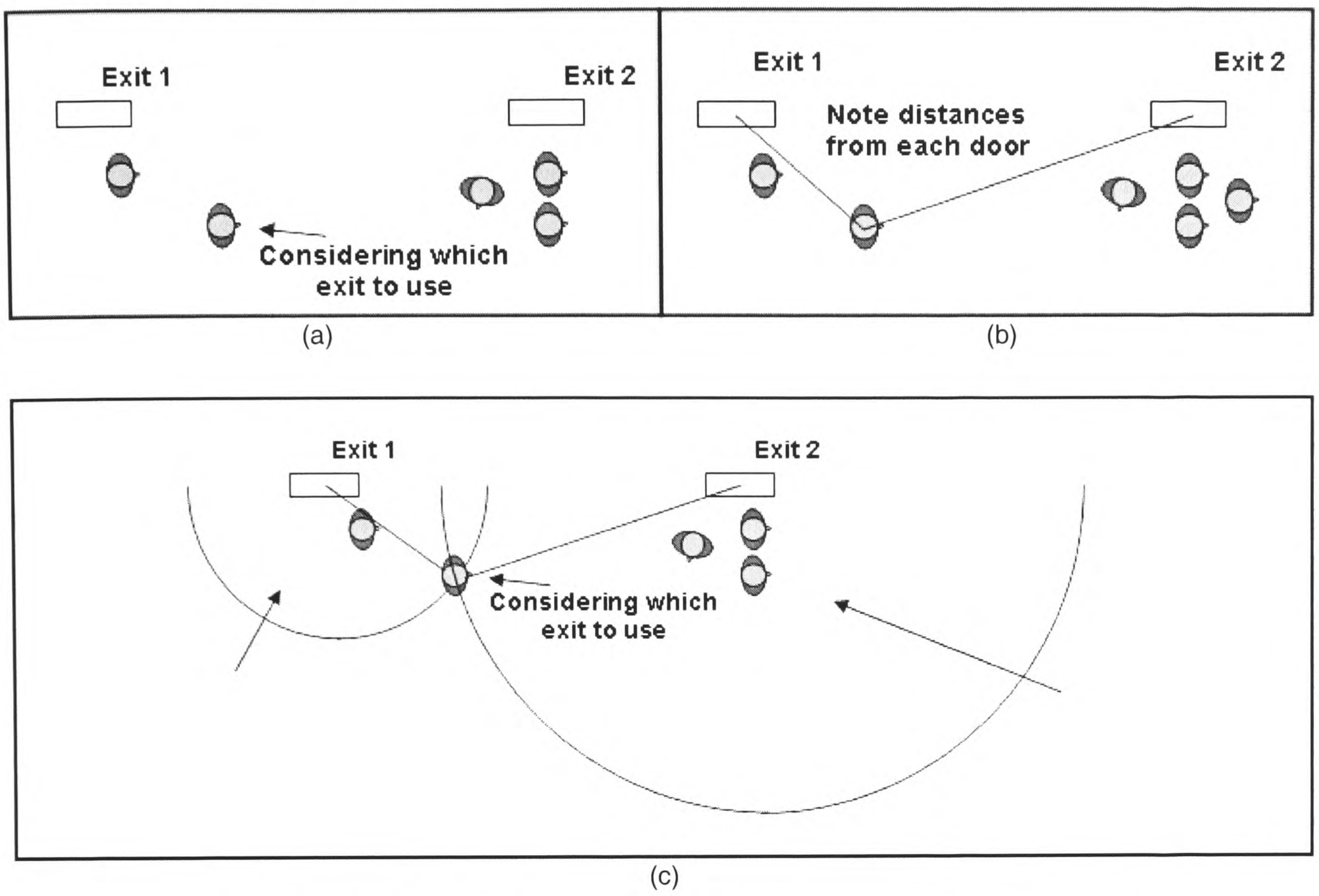


Figure 65: A hypothetical situation demonstrating how the pai,x estimate is derived

A flow rate estimate f is used within the model as a mechanism for passengers to estimate the length of time they are likely to wait given the number of passengers ahead of them. Determining a value for this estimate to use within the model is a difficult task and is likely to be unique to each passenger.

Recall that as part of the cabin crew redirection model the crew were given an estimate of the length of time required to evacuate a single passenger through an exit. The value used represented average flow rates for each exit type derived from past 90- second certification trials [158,159]. In reality passengers would not have the same level of knowledge of exit performance characteristics as members of the crew. Indeed passengers may only have a tentative knowledge that different exits sizes exist let alone their different flow characteristics. This was apparent from the discussion of emergency evacuations in which passengers tended to

Table 40: Static passenger estimate (fi)of the time required to evacuate a single passenger through each exit type

Exit Type	Time required to evacuate a single passenger (seconds/passenger)
Type-A	1
Type-B	1
Type-C	1
Type-I	1
Type-III	2

overrate the evacuation capability of Type-III exits. This topic would certainly benefit from some data collection in future.

As such, it is suggested that within the model passengers do not recognise that different exit types have different flow rate capabilities. However, given the present the lack of data on this area it seems reasonable to assign each passenger a similar flow estimate that can be configured by the user (see Table 40). The flow rate estimate for passengers (*f*) defaults to a flow rate of 1 seconds per passenger for floor level exits (e.g. Type-A, Type-I, Type-B and Type-C). In reality passengers may have some intuitive ranking for a walkthrough (floor-level) exit as compared with an over wing exit. To represent this within the model passengers' estimate of the time taken to pass through these types of exits is doubled, i.e. 2 seconds per passenger.

Ascertaining the exits that the passenger would consider as options during an evacuation is complex and likely based on numerous factors, such as knowledge of the aircraft layout, visual access, etc. Recall that in the crew redirection model the user defines visual regions to reflect line of sight for cabin crew at redirection stations. This was possible as the crew perform bypass from a few set stations onboard the aircraft. Passengers will be making exit choice decisions at any location within the aircraft. Therefore visual regions would need to be defined for every passenger at every stage of the evacuation. This would prove a time consuming task for a user and extremely computationally expensive if calculated automatically. For this reason, a less computational expensive and somewhat simplified representation of visual access has been developed for use in the passenger model. This will be discussed in more detail in a later section.

Firstly, the construction of a passenger's estimate of the likely travel time when using each exit is presented. This estimate is calculated using an adaptation of Equation 17 and is shown in Equation 22. Using the same method outlined in the cabin crew redirection section, a feature of this model is that the passenger analyses the flow pattern within the cabin so as to avoid confluence with other passengers. This assessment operates in a similar manner to that of the crew checking for direct and indirect confluence and adjusting their estimates according to visibility. Thus, unrealistic situations in which passengers redirect into a flow of passengers moving in an opposite direction are avoided.

$$\boldsymbol{TT_{p,i} \quad = \quad D_{p,i} \quad + tp^{c}_{p,i}} \qquad 22$$

$_i$ = the exit

$\boldsymbol{D_{p,i}}$ = the optimal time required for passenger $_p$ to travel to exit $_i$ assuming there is no congestion

$\boldsymbol{tp^{c}_{p,i}}$ = the confluence penalty for passenger $_p$ en route to the exit $_i$

$\boldsymbol{TT_{p,i}}$ = the revised travel time for passenger $_p$ en route to exit $_i$

$$\boldsymbol{TT'_{p,i} = Max\ (TT_{p,i},\ T_{p,i}\ )} \qquad 23$$

$\boldsymbol{TT'_{p,i}}$ = the revised estimated finish time of passenger $_p$ for exit $_i$

Similar to the crew redirection model, an estimate of the time to evacuate is calculated as the larger of either, the time required for those passengers in front of the passenger to evacuate, i.e. T, or the travel time required for the passenger to reach the exit, i.e. TT. This is shown in Equation 23.

Equation 23 offers a mechanism by which a passenger assesses the merit of using each exit. By contrasting the estimate for each exit, the passenger can determine the exit that offers the lowest personal evacuation time, i.e. the exit that generates the smallest $\boldsymbol{TP_{p,i}}$, see Equation 24.

$$\boldsymbol{I_{p,i} = min(\ TP_{p,i})} \qquad 24$$

$\boldsymbol{I_{p,i}}$ = the exit $_i$ that the passenger $_p$ determines will yield the fastest evacuation time

In reality passengers would be unable to detect very small differences in the time for evacuation routes, i.e. 0.1 seconds, 0.002 seconds, 2 seconds etc. Thus, within the model a threshold for their judgement has been imposed. Within the model passengers will only recognise the need to change route where the difference is between their current route and the new route is greater than 5 seconds.

To summarise, a method has been developed for passengers to determine the best exit to use for their **personal** evacuation. A flow diagram of this model is shown in Table 41.

The scheme involves each passenger estimating the time required for their evacuation through each of the available exits. Information gathering at this stage is totally effective - the next section details a method of limiting dynamic information using a simplistic visual scheme.

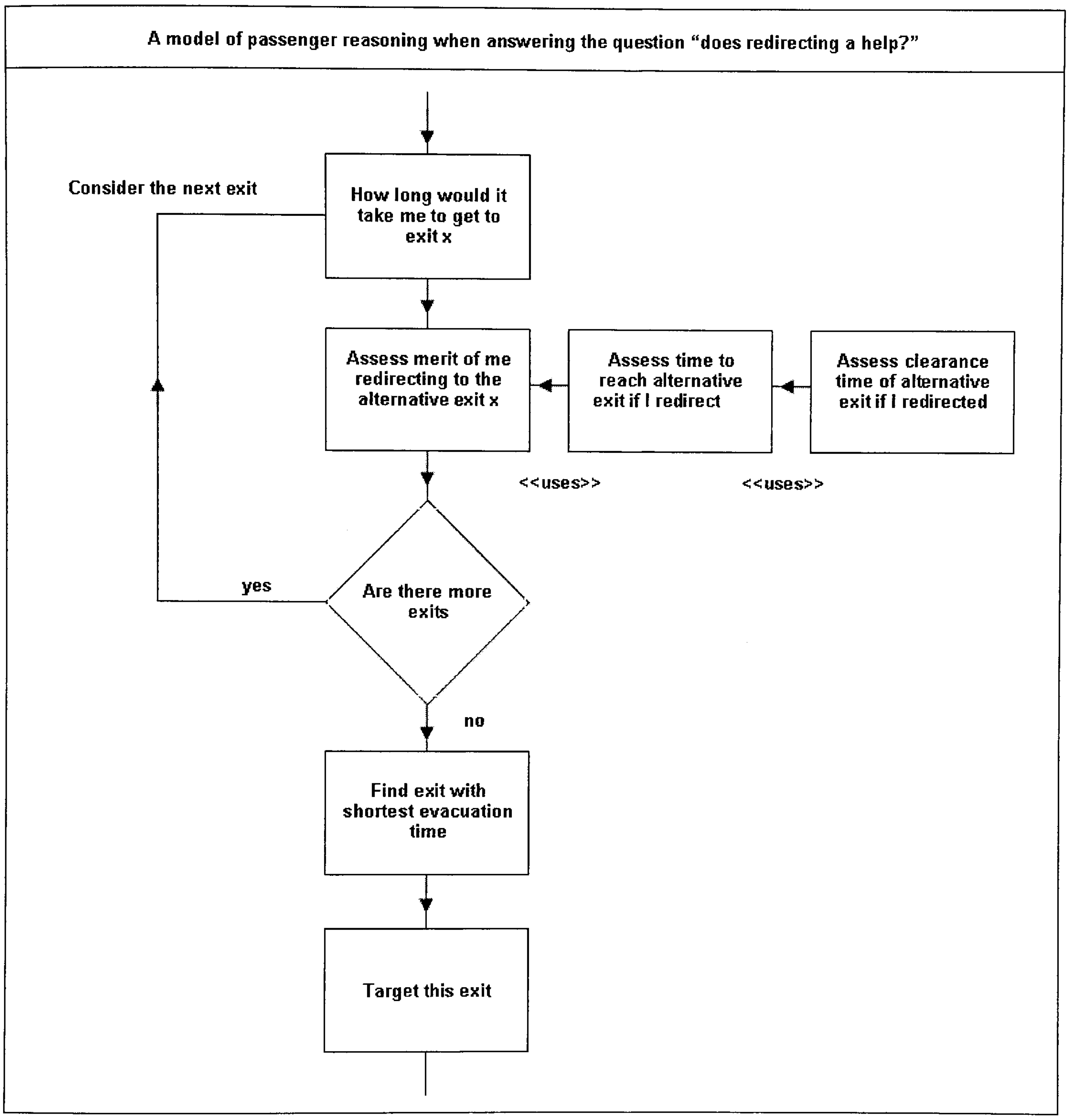


Table 41: Flow chart of a passenger exit choice model

A representation of passenger visual access

In reality passengers would not have total knowledge of dynamic events within the aircraft cabin. Indeed their visual access would be dependant upon numerous factors such as, the ambient lighting within the aircraft, environmental conditions (smoke/fire), visual capabilities of the individual, height of the individual, the height and location of fellow passengers and the geometric configuration of the aircraft, i.e. seat heights, overhead stowage bins and partitions, to name but a few. The complexity of the real world assessment needs to be reduced to a level that is amenable to computer simulation. Line of sight calculations for each passenger are clearly not realistic for this model given the current limitations of computer resources. Furthermore modelling all of these factors would introduce numerous additional parameters into the model, over complicating its use and provide a level of detail that would likely be in excess of the model's sensitivity. A simplified method is therefore developed in this work.

Within the prototype passenger redirection model dynamic information is only used when considering the number of potential competitors for an exit and the flow pattern within the cabin (e.g. confluences). A simplistic method of limiting passenger vision within the model could be achieved through the use of a coarse network representation of the spatial components within the aircraft (see Appendix B). Using a coarse network, passengers could be assigned knowledge of specific spatial components appropriate to their location and the structural configuration of the aircraft. Whilst offering only an approximation of visual access, the approach would be computationally inexpensive and thus capable of running in near to real-time. Furthermore, whilst the method is only an approximation it facilitates the required functionality. Using the coarse network, a rudimentary representation of line of sight can be attained through a few simple rules. Indeed this approach is employed within the prototype model.

Within the model it is assumed that passengers that are considering alternative exits assess the number of other passengers that are closer and likely to use the exit before them. An approach for determining this has previously been developed based on the time it would take them to reach each exit. However, in performing this calculation their overall visibility needs to be limited according to the visual accessibility of the structure. Assuming the passenger is of average height and possesses average visual capabilities, it is reasonable to assume that in clear air the average passenger would be able to see along a series of straight aisles. In addition seating and opposite aisles within the same cabin zone would also likely be visible. Opposite aisles and seating beyond the current cabin zone is typically obscured by the presence of monuments between cabin zones. At a basic level, these three assumptions determine visual accessibility for a 'typical' aircraft. Issues relating to passenger heights are not considered at this stage as they would provide an excessive level of functionality for this portion of the model and an associated increase in required computational resources. Environmental influences, such as smoke, are dealt with in a later section.

Within the prototype model passengers are only concerned with those other passengers that could possibly hinder their access to the exit. In this portion of the model the term visibility refers to visibility of potential exit competitors **only** and not total structural visibility. As such, passengers that have yet to respond, i.e. unbuckle seat belts, are excluded as it is debatable as to whether passengers would not perceive them as viable competitors.

It is proposed that passengers are allowed to have complete access to information within their current spatial component. However, when a passenger attempts to look beyond their spatial component their information is limited. In the prototype model it is limited according to the following rules:

A) Vision is limited to all of the aisles along the shortest route to the exit with the exclusion of the vestibule adjacent to the exit under consideration. Where two aisles are broken by an exit vestibule, the aisles are projected onto the vestibule (see Rule B).

B) Access to information from vestibules other than that which the passenger occupies is limited to nodes that connect the two aisles, i.e. those vestibule nodes that lie on the path through the vestibule.

C) Adjacent aisles and seating sections that are contained within the same cabin zone are considered visible.

In the case of exit passageways through seating, i.e. Type-III exit passageways, the further rule is required that,

These simple rules allow quite complex representations of visual access to be utilised within the model.

Figure 66: A hypothetical narrow-bodied aircraft cabin layout (top) that has been divided in coarse labelled components (bottom)

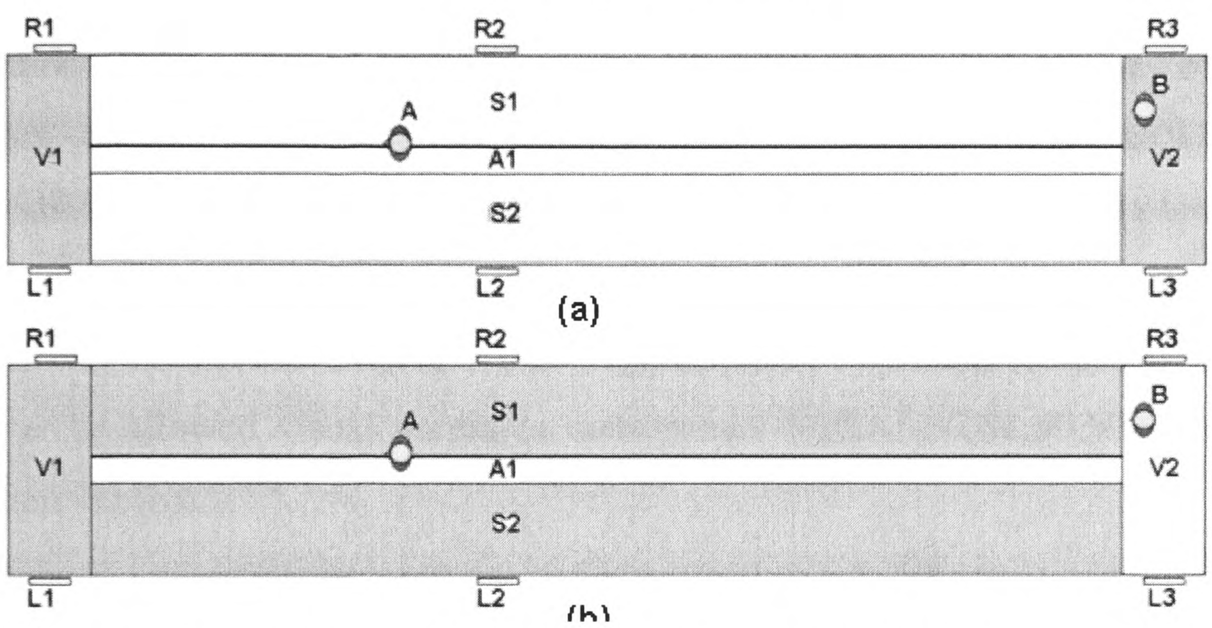


Figure 67: The maximum visibility is the white regions for passenger A (top) and passenger B (bottom) Note -- this may be reduced according to the rules depending upon the exit currently being examined

The application of the rules within the model is best demonstrated with examples. Consider the example in Figure 66. Passenger A and B are considering the merit of using exits R1, R2 and R3. In making their decisions information is limited according to the three rules. Thus, when considering the R1 exit passenger A would have his information limited to {A1,S1,S2} only (Rule B includes A1 and S1, Rule C include S2), whereas for R2 his information would be limited to {A1,S1,S2} (Rule B includes A1 and Rule C includes S1 and S2) and for exit R3 his information would be limited to {A1, S1, S2} only (Rule B includes A1, Rule C includes S2 and S1). When considering exits R1-R3 passenger A would only ever be allowed visual access to components A1, S1 and S2 (see Figure 67(b)).

In the same example passenger B is also considering exits R1-R3. When considering R1 and R2 his information would be limited to {A1} only, whereas when considering

R3 his information is limited to {V2} only. Thus, when considering exits R1-R3 passenger B would only ever be allowed visual access to components A1 and V2 (see Figure 67(b)).

Consider the more complex wide-bodied example in Figure 68, passengers A and B are considering the merit of using exits R1, R2, R3 and R4. Using the proposed rules passenger A's information is limited to only the vestibule and the nearest aisle to the passenger, i.e. {V1} when considering redirection to R1, {V1,A1} when considering R2, {V1,A1,V2,A3} when considering R3 and finally {V1,A1,V2,A3,V3,A5} when considering redirection to R4. By contrast passenger B would have access to information from {A5,A6,S7,S8,S9,V3,A4,V2,A2} when considering exit R1, {A5,A6,S7,S8,S9,V3,A4} when considering exit R2, and only {A5,A6,S7,S8,S9} when consider the R3 and R4 exits. Thus, when considering exits R1-R4 passenger A would only ever be allowed visual access to components {V1,A1,A2,V2,A3,A4,V3,A5,A6 } (see Figure 69(a)). Whereas passenger B would only ever be allowed visual access to components {A5,A6,S7,S8,S9,V3,A4,V2,A2} (see Figure 69 (b)).

Based on the location of passengers in Figure 68(c), passenger A would conclude that one passenger is ahead of him when using exit R1, i.e. $pa_{A,R1} = 1$. The remaining determinations of the number of passengers based on passenger A in are $pa_{A,R2} = 4$, $pa_{A,R3} = 7$ and $pa_{A,R4} = 9$.

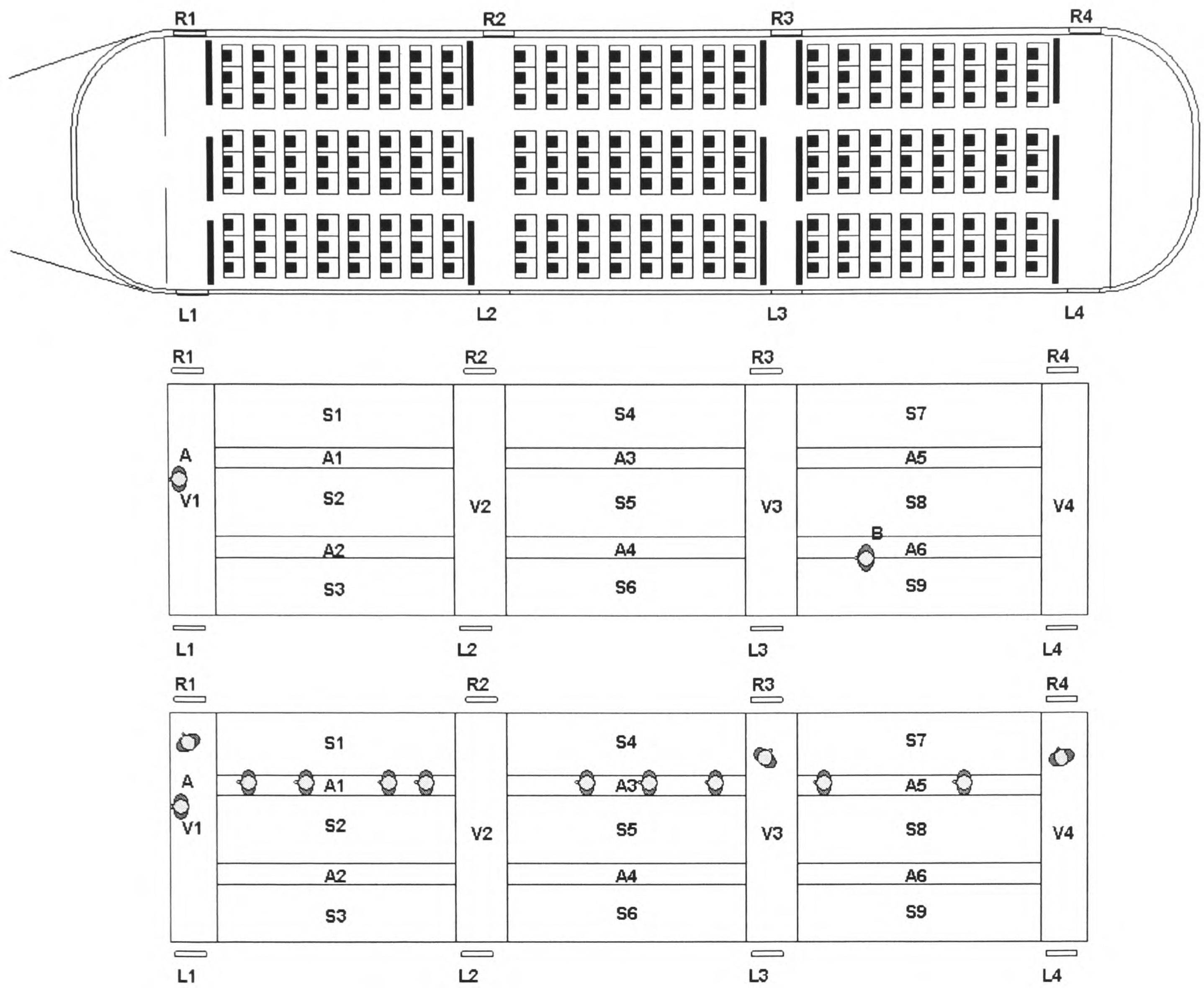


Figure 68: A hypothetical wide-bodied aircraft cabin layout (top) that has been divided in coarse labelled components (middle and bottom)

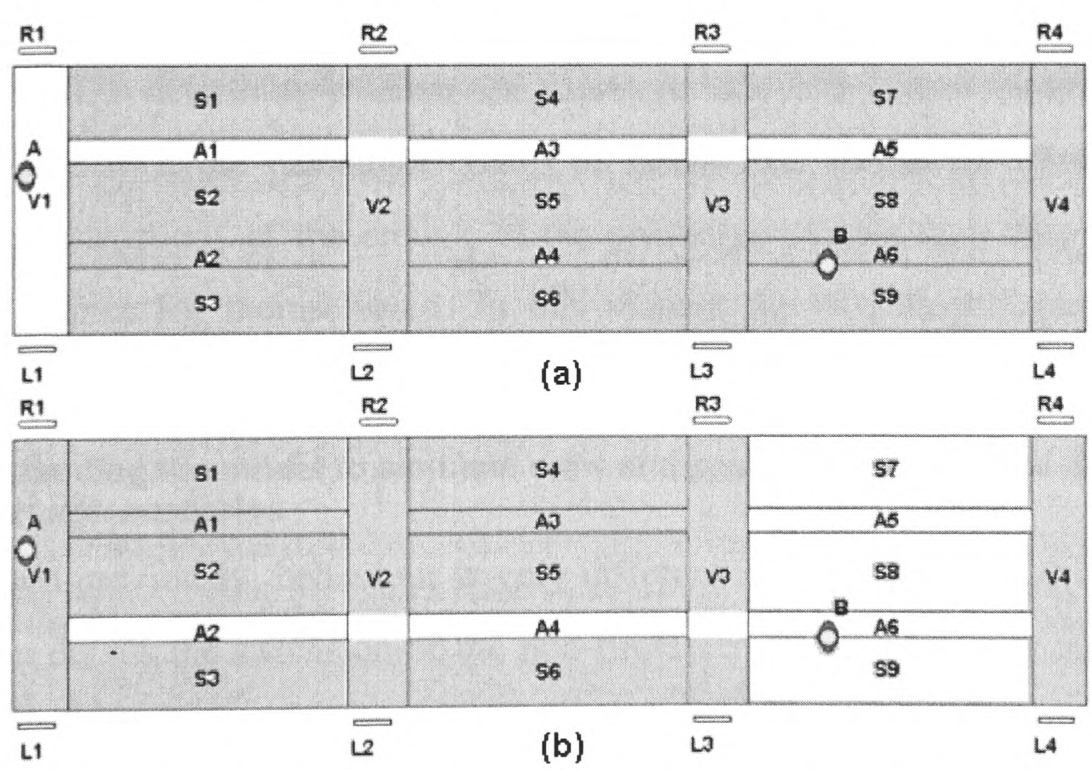


Figure 69: The maximum visibility is the white regions for passenger A (a) and passenger B (b) Note -- this may be reduced according to the rules depending upon the exit currently being examined

Modifications to the cabin crew redirection model

In addition to the development of a passenger exit choice model some minor modifications based on the analysis of the AASK database to the 90-second certification trial crew redirection model are considered important for the model to simulate non-fire/external fire emergency evacuations. In the analysis of data within AASK (Chapter 5) it was suggested that passengers were slightly less subservient to the instructions of crew in real emergencies that did not involve fire penetrating the cabin. In these types of scenarios instances of passenger disobedience were present although relatively rare. Within the prototype model this can be accomplished via temporarily increasing the Drive attribute of every passenger in these scenarios and only affects the passengers' response to crew commands. Within the prototype model it is recommended that the Drive of passengers is only marginally increased albeit by a small margin, arbitrarily 1 Drive point, in non-fire/external fire evacuations.

A method for crew redirection and passenger exit choice to operate in tandem

Finally, it is necessary for the cabin crew model and the passenger redirection models to operate together. From the analysis of the AASK database, it was apparent that passengers initially formed their own exit choice decisions. However, once instructed by a cabin crewmember most people typically abandoned their exit choice and obeyed the instruction of the crewmember.

This could be simulated through allowing the passengers to form their own decisions, however once instructed by a crew member the Drive/Subservience look-up table can be interrogated to determine whether the passenger obeys the crew command. If the passenger does then the passenger ceases to assess exit choice for him/herself and follows the instructions of the crew. If the passenger refuses then they continue to assess exit choice for themselves. In this manner the two models can operate in tandem.

6.1.2.2 Extending the model to simulate crew and passenger exit choice during burn through scenarios

As mentioned previously, behaviour is very different in emergencies that involve fire. This section details the extension of the non-fire/external fire passenger and crew and passenger decision-making model to cover burn through scenarios. As part of this both the passenger exit choice models are extended to include judgements based on the presence of smoke and to limit dynamic information according to smoke visibility.

Finally, an automatic method of moving between non-fire/external fire behaviour and burn-through behaviour is proposed leading to a unified model of crew and passenger redirection in emergency evacuations.

Extending the passenger exit choice model for burn through scenarios

The main differences in passenger exit choice during burn through fire scenarios originate from the hostile environmental conditions affecting the physiology, psychology and toxicology of passengers and crew. These effects have been described previously (see Section 5.4.1) and so will not be discussed again in this section. However, the model is extended to include some of the physical and psychological affects that originate from the presence of a thermo-toxic atmosphere.

An important conclusion from the analysis of burn-through evacuations was that the psychology of passengers is different to those evacuations without internal fire penetration. In burn-through scenarios it was concluded that passengers are less likely to obey the commands of crew. It is therefore recommended that passenger motivation be increased further in emergency evacuations that involve fire penetrating the cabin. Within airEXODUS this could be achieved via increasing the Drive attribute by a large amount in order to reflect the increased urgency of the evacuation. The actual amount of the increase is arbitrarily recommended to be 9 additional Drive points within the model on top of the 1 additional Drive points from the non-fire and external fire model. Thus, the total Drive increase for passengers in burn through scenarios when compared against 90-second certification trials is 10 Drive points.

Another important environmental effect on the passenger exit choice model – and indeed the crew redirection procedure - is that smoke and acidic toxic gases would limit visual abilities. Thus, in order to represent passenger exit choice in burn through scenarios it is necessary to limit visual access according to the atmospheric conditions within the aircraft cabin. Smoke and fire completely blocking a route is the subject of future work and is already partially considered within standard airEXODUS V3. Reductions to passenger movement velocities is also already included in the standard airEXODUS V3 software [40].

The introduction of a smoke visibility algorithm within airEXODUS

This section details the development of a new method to simulate passenger vision in smoke environments. This will further limit the vision of passengers as determined via the spatial access rules in the previous section. In this section models are developed to represent passenger and crew visibility of exit signs and people in smoke environments.

Limited experiments have been performed using human test subjects in various smoke environments [146]. These have established some understanding of human visibility in various irritant/non-irritant smoke atmospheres (see Section 2.4.3.3). These experiments suggest that passenger vision in smoke environments is person specific [146] and dependant upon on the physical characteristics of the smoke [146].

A commonly used measure of the properties and concentration of smoke is known as the extinction coefficient. The extinction coefficient represents the sum of the scattering and absorption coefficients. The scattering coefficient is a measure of the loss of light per unit distance by scattering and the absorption coefficient is a measure of the loss of light per unit distance by absorption. Thus, an extinction coefficient can be used to represent the different properties of smoke with respect to light transmission and, as it will be shown, to some degree visibility in different smoke environments. The higher the extinction coefficient the denser the smoke and the more difficult visibility would become (see Figure 70).

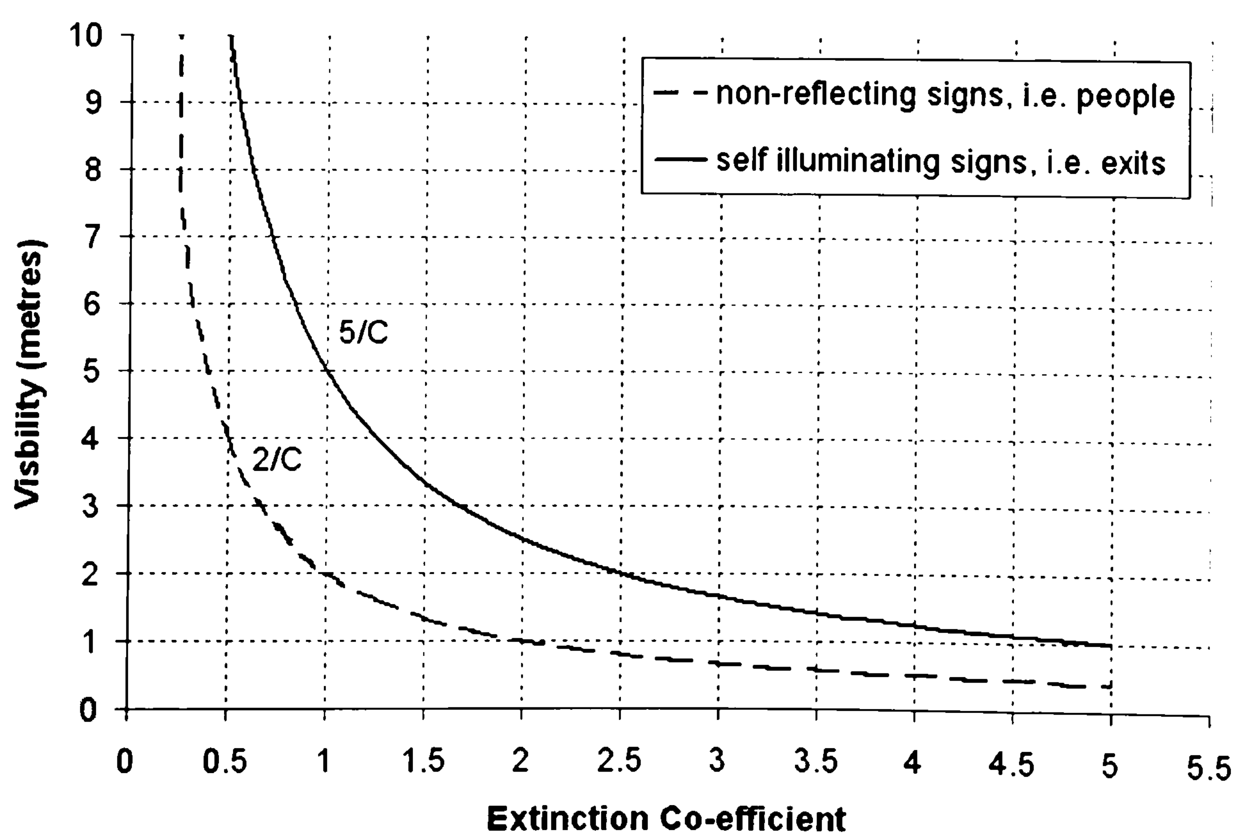


Figure 70: Relationship between visibility and extinction coefficient. Jin [146]

In 1978, Jin presented the results of studies into visibility through fire and smoke. This research involved testing volunteers' ability to see light reflecting and self-illuminating signs whilst being subjected to irritant and non-irritant white and black smoke. Jin concluded that in non-irritant smoke visibility had a constant inverse proportional relationship to the extinction coefficient. Jin concluded that visibility at the obscuration threshold - the maximum visible range that reflecting signs could be seen in non-irritant smoke - could be calculated as:

$$\textit{Visible range} = \alpha / C \qquad (25)$$

Where C = the extinction coefficient

Where $2 \leq \alpha \leq 4$

Whilst this data was appropriate for reflecting signs, Jin stated that,

"The visibility of other objects such as walls, floor, doors stairway, etc. in an underground arcades or a long corridor varies depending on the building configuration and the wall condition, however, the minimum value for reflecting signs may be applicable."[146]

The lower bounds may therefore be appropriate for people in aircraft and provides a method for calculating a visible range in non-irritant smoke conditions. With respect to irritant smoke conditions; his results are less useful. Only data relating to the obscuration threshold of self illuminating signs were provided. However his general conclusions were that visibility was more difficult in irritant conditions whilst showing a similar relationship. For self illuminating signs the obscuration threshold was decreased by 56% from 8/C metres in non-irritant smoke to 4.5/C in irritant conditions. However, at high smoke concentrations volunteers were unable to accomplish the experiment, as Jin stated,

> *"In thick irritant smoke the subjects could not keep their eyes open for a long time, and tears ran so heavily that they could not see the words on the signs."[146]*

Thus, no data was available beyond extinction coefficients of 0.5.

Whilst Jin's conclusions on the obscuration threshold of reflecting signs in non-irritant smoke conditions is used within a model to define the maximum visible range of exit signs and doors for both passengers and crew, the data on non-reflecting signs (lower values are suitable for walls, doors, i.e. people) in irritant smoke was not provided. Given the lack of data, the decision was taken to limit the model to visibility in non-irritant conditions at this stage.

Using Jin's data visibility can be calculated for an individual within airEXODUS via calculating the obscuration threshold, hereafter referred to as the visible range, for each passenger. This requires knowledge of the extinction coefficients within the environment. Presuming that coefficients are the same, then a visible range in non-irritant smoke can be calculated as:

$$\textit{Visible range of walls, people, etc} = 2/C \textit{ metres} \qquad 26$$

Where C = the extinction coefficient

However, a fire does not generate uniform extinction coefficients at every space within an enclosure. A crude method of calculating the overall extinction coefficient between two points is to average the coefficients that lie between the two points. This method, assumes that the affects of varied extinction coefficients can be averaged over space. With a nodal model, such as airEXODUS, extinction coefficients are recorded at every node. These values are labelled as X_1 , X_2 ... X_x (see Figure 71). In nodal models the distances between these points are typically represented by arcs λ_1 , λ_2 ... λ_i of specific lengths. From these an average extinction coefficient ($\bar{x}$) can be calculated between any two adjacent nodes.

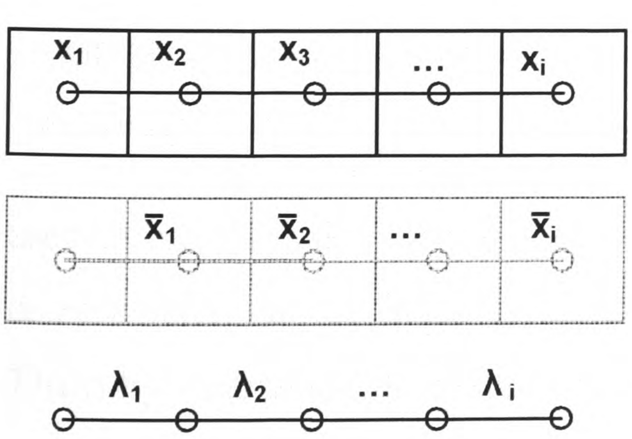


Figure 71: Extinction coefficient notation for calculating the visible range

Similarly the average extinction coefficient can be calculated between a series of nodes via weighting the coefficients according to the length of the arc λ_i that connects the two nodes (see Equation 27). Given Equation 27 the visible range for a passenger can be calculated via equation 28. Using this an algorithm appropriate to calculating visibility in nodal models is developed (e.g. Equation 28 describes one method). The method has been designed so that it limits computational expense and is explained via the use of a hypothetical scenario shown in Figure 72.

$$\frac{\sum_{i=1..n} \bar{x}_i \cdot \lambda_i}{\sum_{i=1..n} \lambda_i} \qquad 27$$

Where x_i = Extinction coefficient x of node i

$\bar{\mathbf{X}}_i = (X_i + X_{i+1})/2$

λ_i = the distance between each node i and node i+1

$$\alpha \Big/ \left(\frac{\sum_{i=1..n} \bar{x}_i \cdot \lambda_i}{\sum_{i=1..n} \lambda_i} \right) \qquad 28$$

α = 2 for reflecting signs, i.e. people and

α = 5 for self illuminating signs, i.e. exits

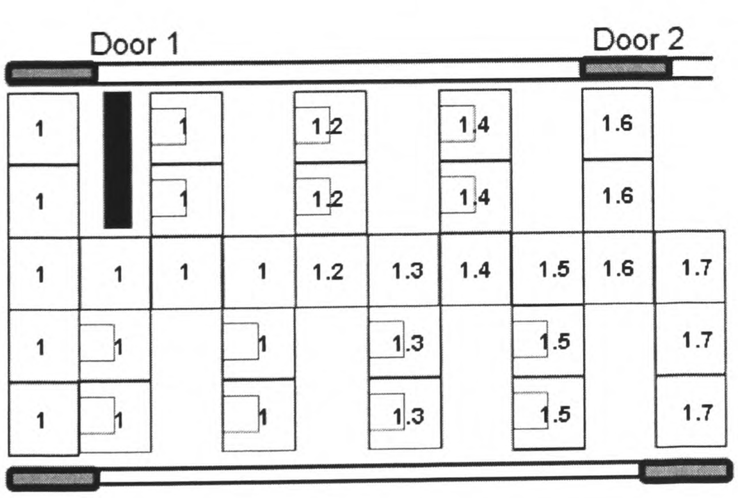


Figure 72: Hypothetical cabin section with extinction coefficients (X) shown at each node

The procedure involves calculating an average extinction coefficient between the person and each node within the aircraft (see Figure 73(b)). Within the model the calculations begin at the node occupied by the person and propagate outwards. This allows previously calculated values to be used to calculate the each successive node thus limiting computational expense. A determination can be made as to whether a node is either visible or not (see Figure 73(d)) by contrasting the distance that each node is from the person (see Figure 73(a)) against the visible range across the distance between the person and each node (see Figure 73(c)). The prototype method further limits the number of calculations by contrasting the distance of each node from the person against the visible range at every stage of the calculation. Those nodes that are within visual range are stored in a list and those that are not are stored in a list of frontier nodes. The calculation never progresses beyond the frontier (see Figure 74).

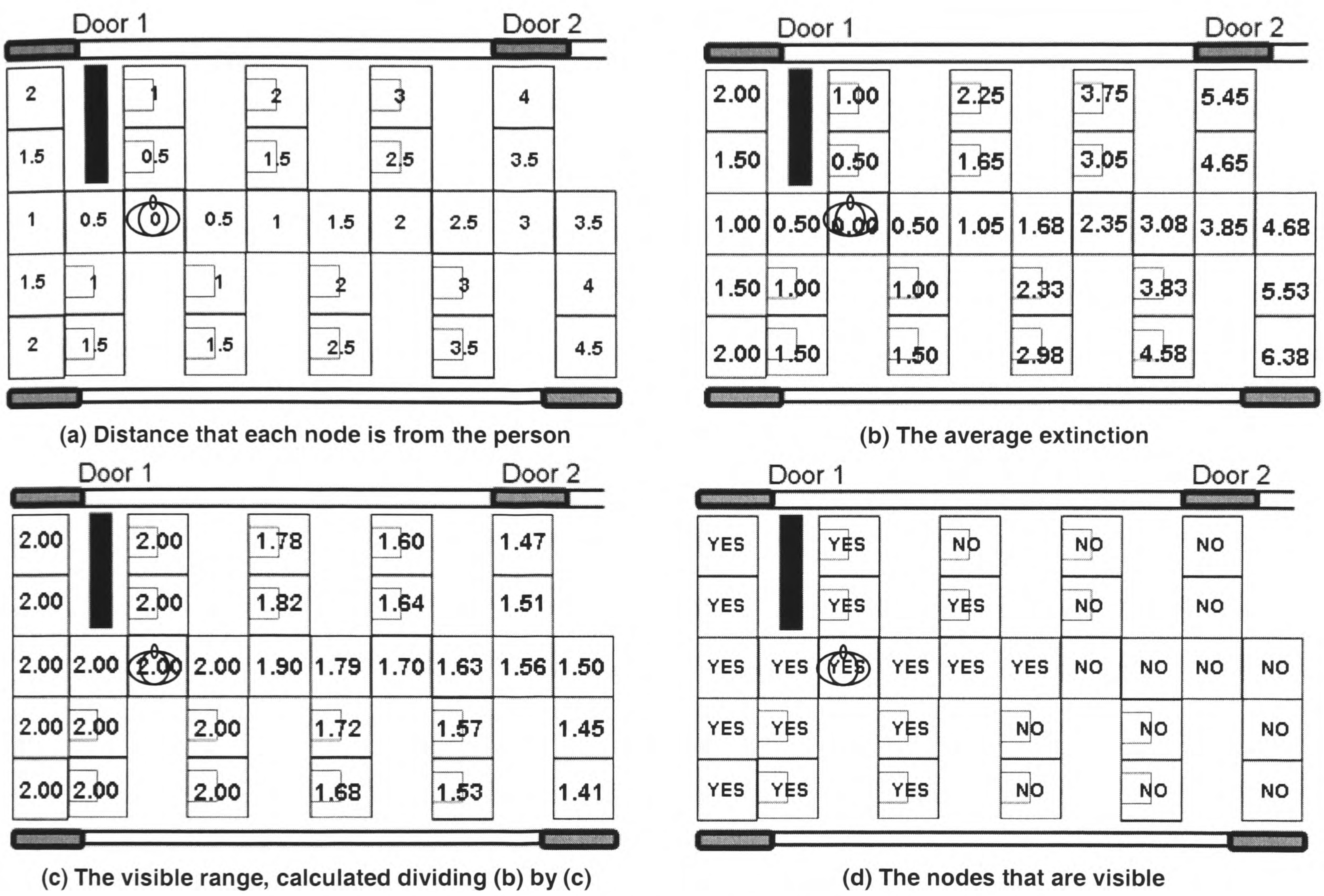


Figure 73: Method for calculating visible nodes for EVERY node

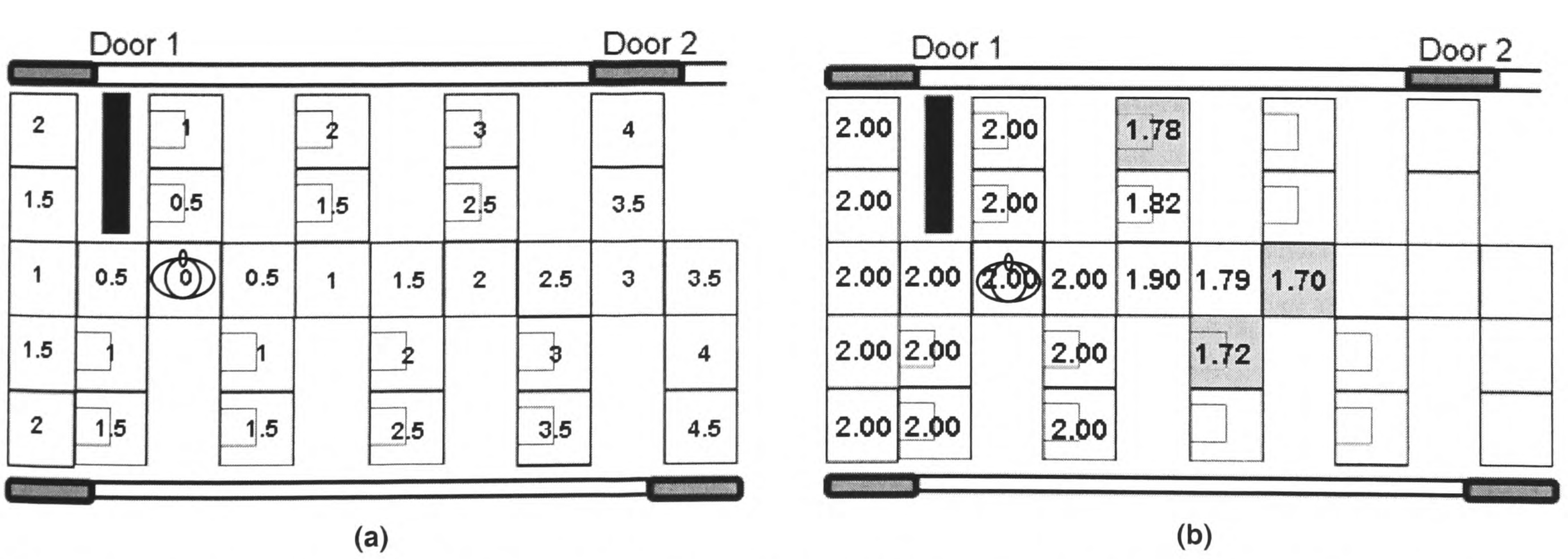


Figure 74: Example of the frontier (gray) node when using method two – a frontier node is a node where (b) < (a)

The smoke visibility algorithm is calculated at every step of the simulation. Dynamic information gained through sight is further limited to those nodes that are included within the list of visible nodes of the passenger. This operates in conjunction with the spatial access visibility methods outlined in the previous sections.

Since airEXODUS stores two extinction coefficients – one for the upper layer and one for the lower layer, visibility is calculated using the smoke value appropriate to their posture, i.e. whether they are crawling or standing. Finally, the smoke visibility algorithm is also used to determine whether exits are visible to passengers and to limit those that they consider during their evacuation. This requires a minor modification to the visible range (Equation 26). Jin provided a function for calculating the visible range of light emitting signs (see Figure 70). A visible range for exits can be calculated via using Equation 29 in Equation 28.

$$\textit{Visible range of exits/door} = 5/C \textit{ metres} \qquad 29$$

Only exits that are within the exit visible range of passenger are considered during exit choice assessments. Situations could occur in which a passenger cannot consider any redirection decisions as they cannot see any exits. In these circumstances the passenger are forced to continue with their original exit choice.

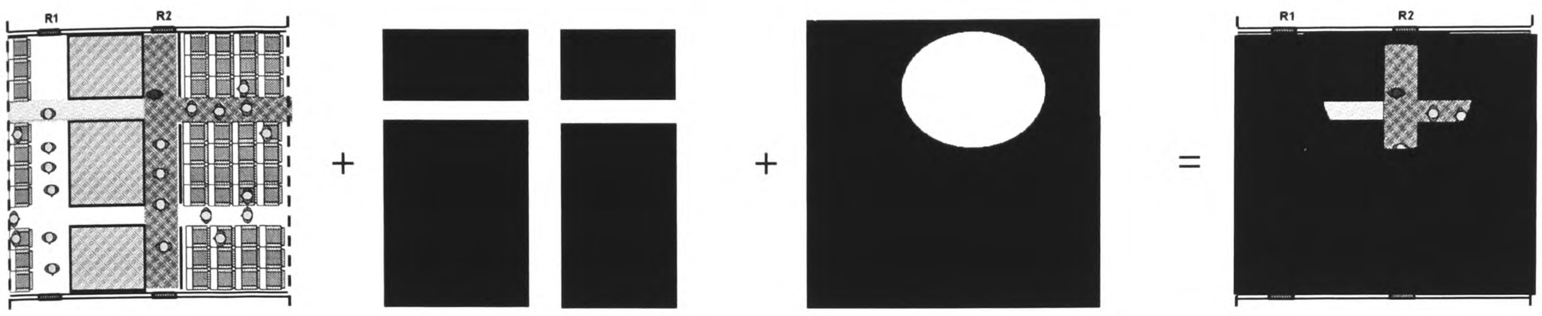
Whilst smoke currently affects the movement rate of people it is also necessary to have people recognise that smoke is present and may present an obstacle to movement [40]. Within the model this is achieved by the adjustment of both passenger and crew estimates of movement velocities to those generated when moving through smoke. Using this approach, passengers and crew would perceive a nearby exit in smoke to be equivalent to a distant exit in clear air. An immediately apparent result of this is that reducing the travel distance to exits becomes of great importance during thick smoke in which movement is slow.

Modifications to the cabin crew exit choice model

As with passengers, the crew may also suffer psychological, physiological and toxicological effects during an evacuation with a thermo-toxic environment. Thus, additional modifications and extensions to the crew redirection model are also required.

An important chemical and biological effect of real emergency evacuations that involve fire penetrating the aircraft fuselage is that the ability of the crew to communicate would be reduced. This is due to the chemical effects of irritant acid gases upon the throat and pulmonary systems in addition to smoke particulate in the atmosphere blanketing sound (see Section 5.4.1). Therefore, the first modification to the cabin crew redirection model in fire scenarios is that the range of crew communication should be reduced. The actual level of the reduction is a matter for further research, however evidence from AASK and accident reports suggest that communication range should be severely reduced. Ideally, experimental research would determine values for these parameters. In a previous section an approximation of the cabin crew effective communication range was discussed and the effective communication ranges were reduced by approximately half in smoke conditions. In addition smoke would also affect the vision of crew in a similar manner to passengers. Thus, crew should also have their dynamic information collection curtailed using the smoke visibility algorithms previously developed. This should operate in conjunction with the crew visible regions approach outlined earlier (see Section 6.1.1.1). Conceptually this can be thought of as applying two different stencils to the geometry (see Figure 75), the structural and smoke visibility stencils. The visible region stencil limits the nodes according to the spatial access within the cabin. The smoke visibility stencil is applied to possibly further limit the available information according to environmental conditions. A key assumption of this model is that the effects of visual accessibility and smoke vision are additive.

Recall that user defined visual access was specified for the crew at every redirection location. The visual access represented vision for a standing crewmember. Should the crewmember be forced to adopt a crouching posture then the visual access afforded by the structure would be altered. Two levels of visual accessibility should therefore be defined within the model – one for a standing crewmember and another for a crawling crewmember. Visual access for crew when crouching has not been implemented within this version and is the subject of further work. The effect of this omission is considered minimal, as in order for a crew to adopt a crouched posture smoke conditions must be severe. Consequently, vision would be extremely limited by the smoke visibility algorithms and the visibility level afforded by the structure is essentially irrelevant. Extending the model to include this feature should not prove difficult.



Total vision + Geometric visibility stencil + Smoke visibility stencil = Total visible passengers

Figure 75: The application of the hypothetical visible region stencil followed by the hypothetical smoke visibility stencil

The result of limiting information according to smoke and structurally visibility is that the number of passengers that are thought to be using particular exits can be highly inaccurate (see Figure 75). This reflects the problems encountered by crew during REAL emergency evacuations involving fire and smoke.

Within the prototype cabin crew model the smoke visibility algorithm is also used to determine the exits that the crewmember is able to see. When considering redirection the crew exclude exits that are outside of their smoke adjusted visual range. Thus, a crewmember may attempt to redirect all passengers towards a single exit. Furthermore, situations could arise where crew cannot see any exits. In this event crew redirect passengers towards the nearest exit.

A further effect of smoke is that the crew should consider the smoke as presenting an obstacle to passenger movement. For example if passengers are being forced to crawl or feel their way through the cabin then the crew should recognise this and factor it into the any redirection decisions. This can be accomplished via using the standard airEXODUS smoke adjusted movement velocities [40] within the time calculations of the redirection models. This would have the effect of making the time required to travel relatively short distances in smoke equivalent to long distances in clear air. This has the affect of changing the emphasis of the model somewhat. For example, as the movement velocity of passengers is decreased reducing the distance that passengers have to travel to the exit becomes a greater priority than balancing the number of passengers using each exit. This emphasis shift is not specifically programmed but emerges from the model as a result of the smoke environment.

As mentioned previously, the psychological impact of fire upon passenger motivation has been represented by increased passenger Drive. This has the affect of making any redirection commands less likely to be obeyed.

6.1.2.3 A method of dynamically selecting behavioral models

Many evacuation scenarios undergo change during the evacuation period – for example, most burn through scenarios start out as external fire scenarios. As the scenario develops, the behaviour of the passengers and crew alters reacting to the changing evacuation scenario. Thus, a dynamic method of passengers and crew reacting to the developing scenario in which the model selects appropriate behavioural models to activate is developed.

This can be accomplished via having airEXODUS automatically sense the environmental conditions at every step of the simulation. A simple method is for the environmental conditions at every node to be checked at every second of the simulation. The current conditions are then used to determine the behaviour rules that are used. Should non-ambient conditions be detected, then a fire is assumed to be present within the cabin and the scenario and behavioural options are adjusted automatically by the model to those appropriate to burn-through scenarios. If all of the nodes within the aircraft have ambient conditions then the behavioural switches are configured for non-fire or external fire responses. Conditions during 90-second certification scenarios do not undergo change during the evacuation, as such the behaviour rules during these scenarios would remain static throughout.

6.1.3 Summary of passenger exit choice and crew redirection model development

To summarise, this section has developed a model capable of simulating crew redirection during 90-second certification trials and real evacuations both with and without fire. The model is adaptive and contains features such as simulated vision, based on the visual accessibility of the structure, and smoke conditions within the cabin. Furthermore the model contains a representation of crew to passenger communication.

In addition, a model of passenger exit choice has been integrated for use in real emergency scenarios. Again this model is adaptive representing passenger vision in both clear air and smoke conditions. Both models have been integrated to provide a unified model of passenger and crew exit decision-making. Using these models passengers and crew are constantly making decisions during the evacuation. Finally, a method has been developed that allows the behavioural responses of crew and passengers to respond to the developing evacuation scenario.

Previously in evacuation modelling passenger movement was largely governed by local considerations only. These models have given simulated crew and passengers long term planning capabilities with respect to their evacuation. Using these models, both passengers and crew are able to form decisions about the best strategy for evacuation. Their behaviour has been enhanced so that the reactions of the passengers and crew are not entirely determined by local conditions but are also influenced by global/long-term considerations which contribute to the development of escape strategies.

6.2 Model demonstrations

6.2.1 Large scale demonstration on a wide-bodied aircraft

This section investigates the application of the prototype model to a wide-bodied aircraft evacuation. The aircraft is configured exactly the same as validation Case 4 which held 440 passengers, however in this design a reduced passenger capacity of 400 passengers was tested. During the certification trial this was achieved via leaving alternate seats empty in the first class cabin section at the front of the aircraft. The forward Type-A exit were therefore likely to finish evacuating passengers before the remaining three exits – even if all of the passengers in the forward zone use the front exit. Some form of bypass is beneficial to optimise the certification evacuation for this aircraft.

The set of scenarios that are presented in this section are designed to demonstrate the crew redirection models that have been developed. As such, relatively simple scenarios are used so that the effects of the prototype models can be distinguished and discussed. The final chapter of this thesis describes the application of the prototype models being used in a more comprehensive and realistic safety analysis context.

In total 4 sets of evacuation scenarios are simulated (see Table 42) with each set incrementally increasing the complexity of the prototype models that are used.

Table 42: Summary of demonstration scenarios

Scenario	Scenario Type	Summary of model configuration used
1	90-seconds certification trial conditions	An optimal manner using the standard airEXODUS V3.0 features
2	90-seconds certification trial conditions	Evacuation in 90-seconds certification trial conditions with one crew with perfect knowledge and making perfect decisions
3(a)	non-fire emergency conditions	An evacuation in emergency conditions using the passenger exit choice model without a fire and without crew
3(b)	non-fire emergency conditions	An evacuation in non-fire emergency conditions using the passenger exit choice model with one crew making perfect decisions and having perfect knowledge
3(c)	non-fire emergency conditions	An evacuation in non-fire emergency conditions using the passenger exit choice model with two crew making perfect decisions and having perfect knowledge
3(d)	non-fire emergency conditions	An evacuation in non-fire emergency conditions using the passenger exit choice model with two crew making imperfect decisions and having imperfect knowledge
4(a)	Severe emergency conditions	An evacuation in severe fire emergency conditions using the passenger exit choice model with two crew making imperfect decisions and having imperfect knowledge without smoke
4(b)	Severe emergency conditions	An evacuation in severe fire emergency conditions using the passenger exit choice model with two crew making imperfect decisions and having imperfect knowledge with a uniform smoke atmopshere

The first scenario simulates a standard 90-second certification trial for this aircraft configuration without using the models developed in this work. This establishes a base-case against which the results of the later simulations that use the prototype models are contrasted. Scenario 2 investigates the same model configuration as Scenario 1, except that a single crew is modelled in the L2 exit area and is assigned redirection duties.

Scenarios 3 and 4 demonstrate real accident scenario. Four sub-variations of non-fire real emergency evacuations are modelled to demonstrate the sensitivity of the model to cabin crew numbers and their efficiency. Scenario 3(a) establishes a base-case for this scenario via repeating Scenario 2 however this time under non-fire emergency conditions without any cabin crew and using the passenger exit choice model. Scenario 3(b) re-evaluates scenario 3(a) however with a single cabin crew member defined similar to Scenario 2. Scenario 3(c) demonstrates the sensitivity of the model to the number of cabin crew members via adding an additional crew member into the model. Finally, Scenario 3(d) demonstrates its sensitivity of the model to the efficiency of the crew.

The scenario demonstrates the functionality of the models in severe fire conditions. For simplicity the model configuration used in Scenario 3(d) is used. The first scenario (Scenario 4(a)) simulates severe emergency conditions without smoke whilst Scenario 4(b) simulates severe emergency conditions with smoke.

6.2.1.1 The aircraft configuration

This aircraft seats 400 passengers (40 seats were empty during the trial) in three seating zones with 70 passengers in the forward zone, 204 in the central zone and 127 in the aft zone (see Figure 76). In total the aircraft has 4 pairs of Type-A exits with the central pairs being canted. In these scenarios only the right side exits are active (see Figure 76). The exits are made ready using generalised times taken from 90-second certification trials. Finally, the cabin is populated in accordance with FAR 25.807 requirements. Assertive cabin crew are implicitly modelled at the active exits through the application of the appropriate Exit Delay Distribution.

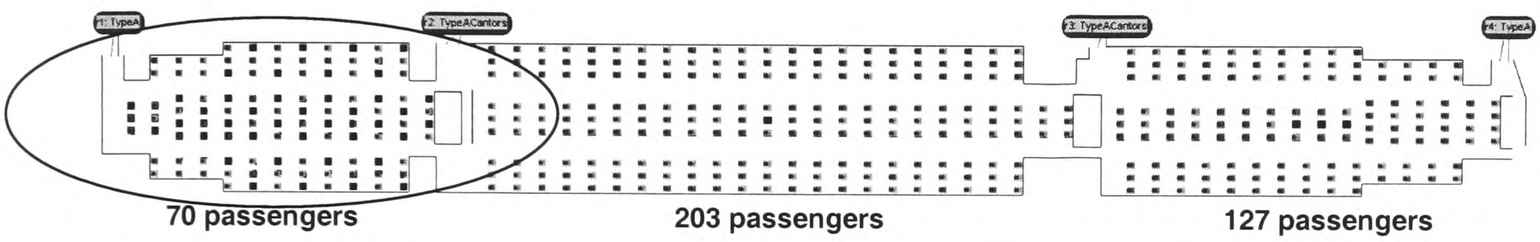


Figure 76: Wide-boided aircraft cabin layout (Alternate seats within the cirlced area were kept empty to simulate a first class-cabin section)

6.2.1.2 Scenario 1: Optimal certification evacuation scenario using standard airEXODUS V3.0 features

This scenario provides a basis for later analysis. The model is configured in an optimal manner using 'standard' airEXODUS version 3.0 features. This configuration represents the functionality of the model prior to this thesis (see Table 43).

Table 43: Model settings for Scenario 1

Version 3.0 of airEXODUS	
Crew features: • Implied crew behaviour; new features not implemented	Passenger Objective: • Follow potential map

In an attempt to attain optimality all of the passengers in the forward seating zone will be directed to the forward R1 exit, a balance between the R2 and R3 exit is attained in the mid-section and nearly all of those in the aft cabin section will be directed to the R4 exit (see Figure 77).

In this scenario all of the passengers used the exits that they were assigned through the potential map and no bypass redirection occurred at any exits. Whilst the aircraft was evacuated in under 90 seconds a high OPS score (OPS > 0.1) indicates that this evacuation could be optimised through better exit utilisation (see

Table 44). This is apparent from examination of the number of evacuees (67 passengers) that used the forward exits as compared to the mid-section (121 and 113 passengers) and the aft exits (99 passengers).

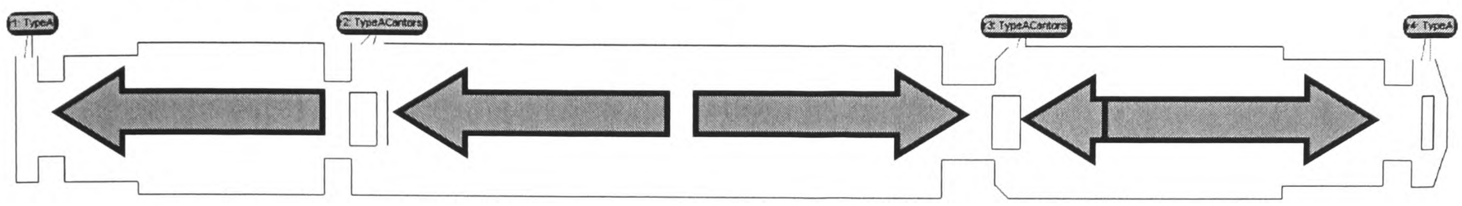


Figure 77: Enforced movement pattern configured within the model through implied crew behaviour

Table 44: Results for scenarios 1 and 2

		TET (secs)	PET (secs)	Evacuees (passengers)				OPS
				R1	R2	R3	R4	
Scenario 1 90-second trial using airEXODUS V3	Min	67.7	36.4	65	120	112	98	0.08
	Mean	71.3	37.8	67	121	113	99	0.13
	Max	76.0	39.2	68	123	115	99	0.18
	STD	1.74	0.51	0.55	0.74	0.78	0.50	0.02
Scenario 2 90-second trial using With one cabin management crew	Min	66.1	36.3	79.0	110.0	106.0	88.0	0.02
	Mean	69.6	37.5	86.3	115.6	109.8	88.3	0.06
	Max	78.7	39.2	93.0	124.0	111.0	91.0	0.15
	STD	1.97	0.5	2.39	2.61	1.16	0.81	0.02

6.2.1.3 Scenario 2: Certification evacuation scenario with one crew with perfect knowledge and making perfect decisions,

In scenario 2 a single crew has been placed at the L2 exit area and given the responsibility of balancing the R1 and R2 exits (see Figure 78). This will involve bypassing some of the passengers attempting to use the R2 exit forwards to the R1 exit.

During the simulations on average 21 passenger and as many as 26 are directed by the crew from the R2 to the R1 exit. In these simulations, the crew ascertains that the R2 exit will soon finish evacuating passengers and so redirects fast moving passengers towards the R1 exit. Whilst doing so the crew was careful not to redirect too many passengers at once but to maintain a flow of passengers to the more local exit (see Table 44).

A more detailed example of a redirection decision within the model is explored through the use of Figure 79. In Figure 78 the crew has already redirected the three left most passengers within the ringed area but is considering redirecting more. In this example the crew has total visual access and as such would determine that 13 passengers are using the R1 exit – 10 from the area adjacent to the exit and 3 previously redirect passengers – and that 48 passengers are using the R2 exit. Using the crew estimate of the flow rate capabilities of each exit the crew determines that the R2 exit will finish evacuating passengers at approximately 27 seconds (48*0.56) and that the R1 will take approximately 7 seconds (13*0.56). Based on these figures the crew estimates that the difference between finish times of the two exits amounts to 20 seconds. As such the crew recognises the need to redirect (difference > judgement, where judgement = 5 seconds).

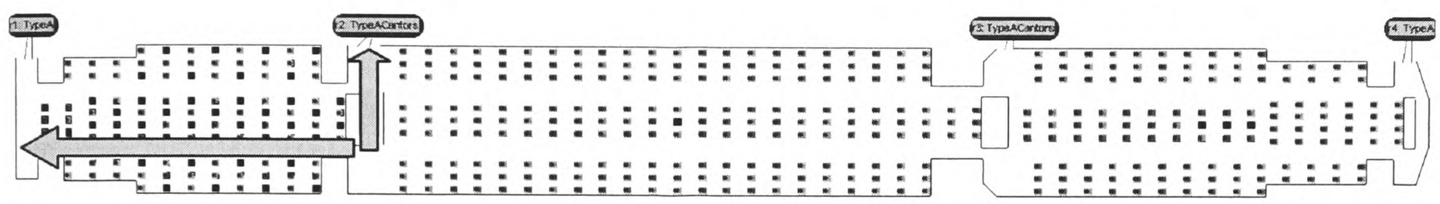


Figure 78: Crew location and duties in Scenario 2 and Scenario 4(b)

Table 45: Model settings for Scenario 2

A 90-seconds certification trial mode using the new algorithms	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses 90-second certification trial Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ TDIS vision representation, i.e. perfect ✓ PERFECT decisions Crew personal parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • Fixed exit flow rates (see Table 38) • Explicit crew model with one crewmember	Passenger Objective: ✓ **ALWAYS** do as instructed

Having recognised the need for redirection the next step in the algorithm has the crew determine the passenger that is best placed to redirect from R2 to R1. In doing so those passengers located within 2.5 metres of the R2 exit are ignored by the rules of the model as they are within the local catchment area of the door (2.5 metres being an arbitrary catchment area set to Type-A exits). Each of the remaining passengers that are currently using the R2 exit and both visible and within communication range of the crew each assessed in turn. In doing so the crew considers the time it would take each passenger to reach the exit plus the number of passengers that could cause confluences alone the route. As such the algorithm favours passengers at the periphery of the R2 exit queue that are also nearest to the target exit.

In the example shown the crew chooses the nearest available passenger to the R1 exit that is not currently using the exit, i.e. the right most passenger in the ringed area. For this passenger an unimpeded estimate of the time required to reach the alternative exit is calculated as 13.58 seconds (distance of 14.94m divided by their travel speed 1.1 m/s). Added to this are confluences along the route, i.e. no confluences as every other passenger *en route* to the exit is using the same exit. The algorithm would then continue this assement for other passengers within range of communication, i.e. those to the right of the ringed area. Whilst their greater distance from the exit maybe compensated for by higher travel speed, they would all have had to move in direct opposition to the right most passenger in the ringed area and thus incur at least one direct confluence penalty. Consequently they would most likely not represent the 'best' option for redirection at this time. Thus, the algorithm would conclude that the passenger best placed for redirection to the R1 exit is the passenger that is the nearest within the ringed area.

Having selected the passenger best placed for redirection to the R1 exit the crew checks that their redirection is worthwhile. To do this, the revised finish time for the R1 exit is calculated. The revised finish time is estimated as the greater of either the time taken for the redirected passenger to reach the exit (e.g. ~14 seconds) or the revised finish time for the exit taking into account the extra passenger (e.g. [13+1] * 0.56 $\approx$ 8 seconds). Similarly a revised finishing time for the R2 exit is calculated by the previous number of exit users minus the redirected passengers multiplied by the flowrate of the exit (e.g. [48-1]*0.56 $\approx$ 26 seconds). Since the revised finishing time of the alternative exit ($T'_{best} \approx$ 14 seconds) is still lower than the revised finishing time of the R2 exit (i.e. $T_{Worst} \approx$ 26 seconds) redirection of this passenger is judged as beneficial to the aircraft as a whole.

Finally a check of the conditions at the local exit is made. In doing so the crew projects the selected passenger's path to the local exit. Since the exit is a floor level exit type, two local override conditions exists: namely the density over the total route to the alternative exit must be < 1 or a 1.5m or greater gap has developed leading to the local exit. In this example the density over the route to the local exit is 1.33 passengers/metre (i.e. 6 passengers / 4.5 metres) and no gap is present. Thus redirection is again confirmed as being worthwhile in this instance.

Finally, the crew decides to redirect the passenger and begins attempts at communication. First the model determines the assertiveness of the crews command. Recall that this simulation is optimal and that the assertiveness of the crew is thus set to maximum. Using this value the model notes that the passenger is within 1 metre range of the crew, hence within touch range. Thus, the touch range assertion levels are used within the model (i.e. no negative modification to the overall assertiveness of the crew applies). The result of this is that in this example the crew assertive level is set to maximum. Thus, within the model the contrast of the passenger's Drive against the assertiveness of the crew always results in a successful redirection attempt and the passenger adopts the wishes of the crew.

The result on overall evacuation performance from the application of these algorithms is that the average TET is decreased by on average 1.7 seconds (2.4%). In this scenario the improved evacuation efficiency results directly from better exit utilisation as reflected by the average OPS of 0.06. This is apparent from in which an aveage of 67 passengers used the R1 exit in Scenario 1 compared with on average 86.3 in Scenario 2.

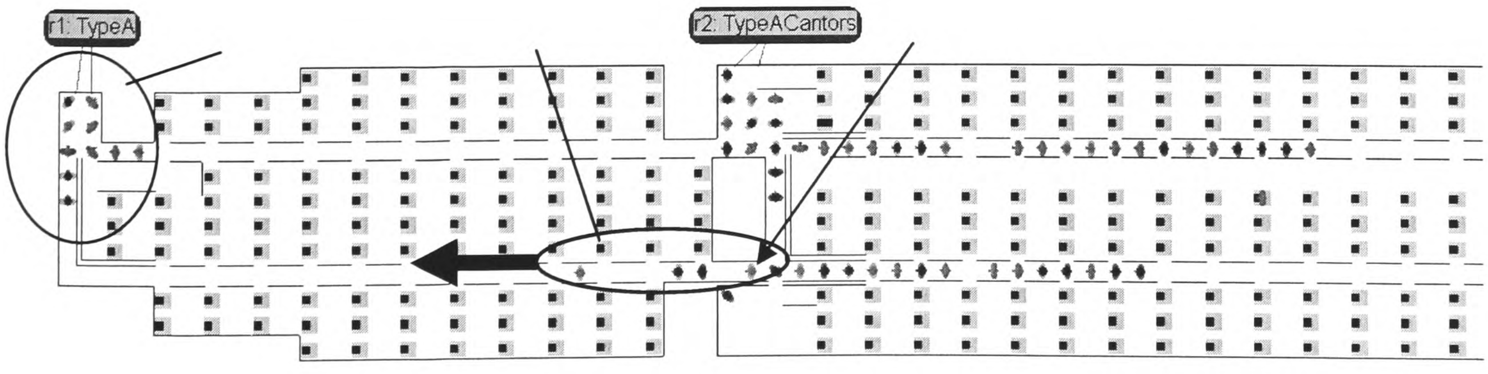


Figure 79: example shows four passenger (circled) being redirected to the R1 exit during the final 15 seconds of the evacuation

6.2.1.4 Scenario 3(a): An evacuation in non-fire emergency conditions but without a fire and without crew using the passenger exit choice model.

This scenario repeats scenario 1 however under emergency evacuation conditions without crew intervention and using the passenger exit choice models (see Table 46).

This case is illustrated to demonstrate the capability of the passenger model's behaviour in an emergency evacuation **in isolation**. In subsequent scenarios cabin crew are introduced to demonstrate the interaction between both the passenger and cabin crew redirection models. However, in this scenario the cabin crew have been removed and the passenger decision-making models activated. All other model parameters have remained the same.

Table 46: Model settings for Scenario 3(a)

Non-fire emergency conditions using the new models	
Crew features: • No crew present	Passenger Objective: ✓ Try to reduce their personal evacuation time via exit selection ✓ <u>Passenger always do as they want</u> ✓ Vision is limited by: ❑ The geometry

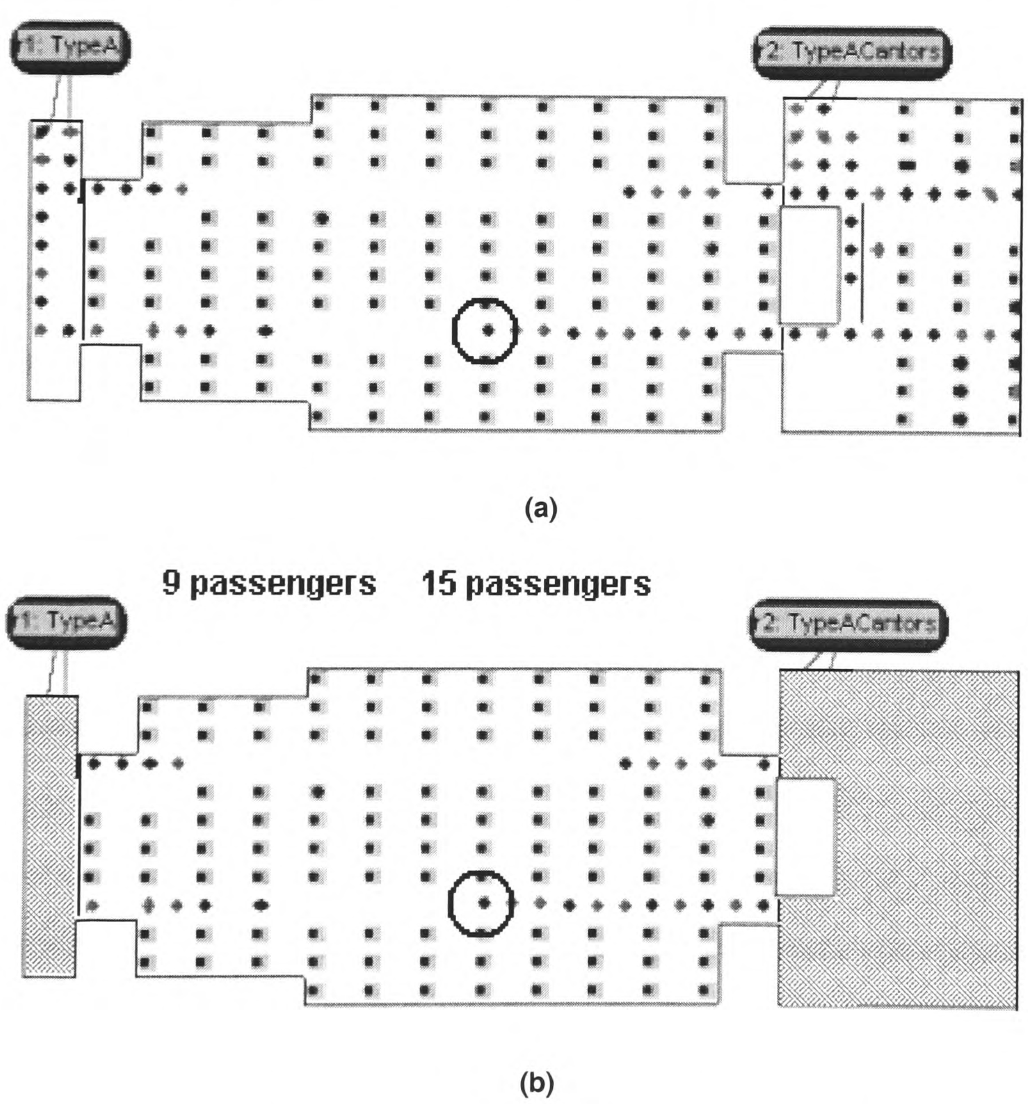


Figure 80: An example of the decision making of a ringed passenger when using the passenger redirection algorithm, (a) shows the cabin and (b) shows the visible area determined via the visibilty algorithms

Since crew are assumed to be absent, all of the exits have been assigned equal attractiveness. Initially this will cause passengers to move towards their nearest exit (see Figure 81) – however as the evacuation unfolds the passengers decision making capabilities may generate more complex behaviour with some redirecting to more distant exits. Mid-way through the evacuation passengers who were at the periphery of exit queues begin to redirect themselves to adjacent exits during these evacuations. Primarily this behaviour occurred in the forward and aft seating sections and involved passengers who were using the mid section exits redirecting to the more distant but under utilised forward and aft exits. Towards the end of the evacuation passenger redirection ceases to occur. This results from them determining that the cabin is emptier than it actually is as a result of the limited visibility imposed by the visibility algorithms.

Again a detailed description of a passenger redirection decision making process is demonstrated. In this example a passenger at the pripherpy of the queue is considering redirection (see the ringed passenger in Figure 80). In doing so the passenger considers all of the exits onboard the aircraft as possibilities. Within the model the passenger forms an estimate based for each exit in turn. When consider the R1 exit the passenger would estimate how long it would take to reach the R1 exit (7.14 metres / 1.05 metres/second $\approx$ 7 seconds). Using this, the passenger next counts the number of visible passengers that may get to the exit before him (9 passengers visible in Figure 80(b)). He then uses a rudimentary knowledge of the exits flowrate to determine that it will take 9 seconds to clear these passengers (9 passengers * a flow rate of 1 passenger per minute). He then notes the negative impact of any confluences along the route to the exit i.e. none for the R1 exit, and adds this to his estimate of the time to reach the exit.

Wihtin the model the passengers estimate for the exit represents the greater of either the confluence adjusted time to reach the exit or the length of time required to evacuate those passengers that will arrive at the exit before him, i.e. 9 seconds.

This process is then repeated for the R2 exit. For this exit, the passenger determines a clearance time of those passenger infront of him as 15 seconds (15 others could reach the exit before * a crude estimate of the flow rate of the exit) and calculates that it will take him approximately 9 seconds (9.42 metres / 1.05 metres/second) – again no confluence along the route exists when using this exit. Thus the passenger estimates that evacuting via the R2 exit would take approximately 15 seconds.

When considering the R3 and R4 exits the passenger is given knowledge of passengers within the aisles *en route* to the exits. As such the passenger determines extremely high levels of confluence along these routes which effectively discount these exits as offering any benefit to his evacuation.

Based on this example, the ringed passenger in Figure 80 would decide to redirect to the exit that he estimates as offering the lowest evacuation time, e.g. the R1 exit.

This process is repreated for all of the passengers withih the cabin. It is interesting to note that (depending on their travel speeds) one or more of the passengers to the right of the ringed passenger would most probably take the decision to redirect to the R1 exit – even if the ringed passenger were to continue using the R2 exit. This would result from the overweighted use of the R2 exit causing passengers to the right of the ringed passenger to determine that using the R1 exit, even with the possibility of incurring a diect confluence with the ringed passenger, still represents a faster option than using the R2 exit.

Returning to the general trends of the passenger redirection model on this scenario. The impact of these models is **a shift in the pattern of exit use during the evolution of the evacuation** from a nearest exit regime (see Figure 82(a)) to a nearest exit use pattern that also reflected the number of users of each exit (see Figure 82(d)). This is indicated by the large grey arrows in Figure 82. During the evacuation none of the passenger seated in the mid-section of the aircraft chose to bypass the R2 or R3 exits of there own accord. The results from the rationale of the passenger decision-making model in which passengers seek to reduce their personal evacuation times. Passengers at the R2 and R3 exit all determined that it would be quicker to queue for the local exit rather than to bypass.

Quantitatively, this scenario generated an average TET of 87.6 seconds and an average OPS score of 0.3 (see Table 47). This represents a large increase on the average TET s generated in the previous two scenarios (71.3 and 69.6 seconds) and results from passengers taking actions that are **best for themselves personally** at ever stage of the evacuation rather than considering the best option for the entire passenger compliment (as in Scenario 2). In addition a higher OPS is generated. The high OPS values reflect the biased nature of the exit use in which 285/400 passengers (71.5%) used the mid-section exits with only 40.9 passengers using the R1 exit compared with 136 using the R2 exit).

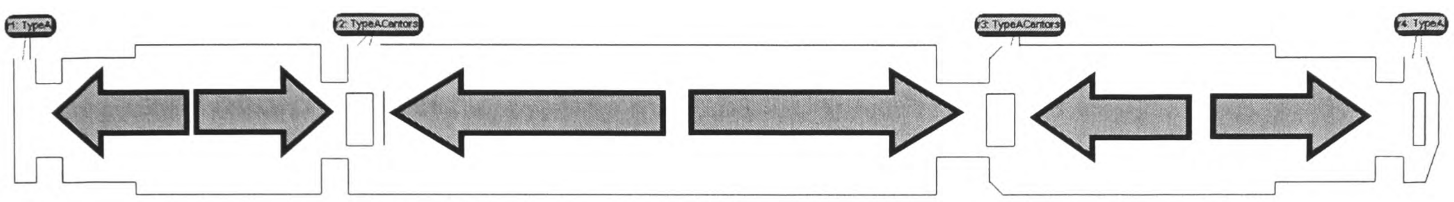


Figure 81: Initial passenger movement pattern

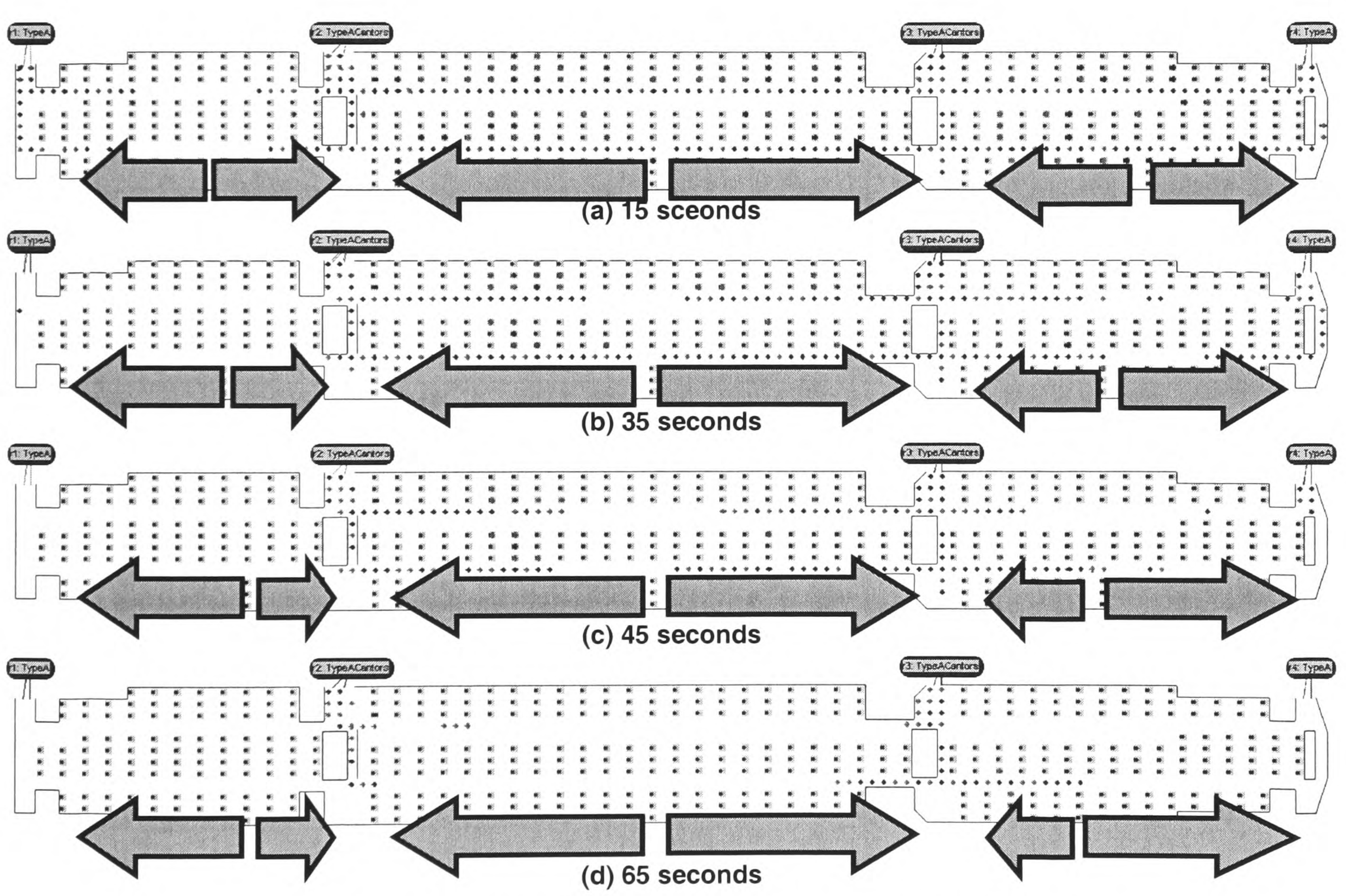


Figure 82: Pattern of exit use during the evacuation in Scenario 3(a)

Table 47: results of the '3' series secnarios

		TET (secs)	PET (secs)	Evacuees (passengers)				OPS
Scenario 3(a) Emergency evacuation without crew	Min	82.1	38.9	38.0	132.0	144.0	70.0	0.21
	Mean	87.6	40.8	40.9	136.3	148.6	74.2	0.30
	Max	94.2	43.8	44.0	141.0	155.0	78.0	0.38
	STD	2.30	0.78	1.35	2.08	2.60	1.81	0.04
Scenario 3(b) Emergency evacuation With one cabin management crew	Min	74.5	37.2	54	116	125	81	0.06
	Mean	82.0	38.8	58	122	132	88	0.16
	Max	91.6	40.3	62	129	138	92	0.30
	STD	3.44	0.59	1.53	2.62	2.38	1.85	0.04
Scenario 3(c) Emergency evacuation With two cabin management crew	Min	71.6	37.4	61.0	104.0	109.0	93.0	0.06
	Mean	81.8	38.7	69.5	113.0	117.7	99.8	0.15
	Max	93.1	40.3	75.0	120.0	125.0	106.0	0.26
	STD	5.1	0.6	3.3	3.5	3.5	2.8	0.05

6.2.1.5 Scenario 3(b): An evacuation in non-fire emergency conditions with ONE crew making perfect decisions and having perfect knowledge using the passenger exit choice model.

This configuration deploys **a single crew member** in the same location and with the same exit responsibilities as Scenario 2 (see Figure 78). This scenario is designed to demonstrate how the passenger decision-making model and cabin crew redirection model interact in an non-severe emergency evacuation. For simplicity and consistency a **single crew member** is placed in the R2 exit vestibule and is configured similarly to Scenario 2. As in Scenario 2 an optimal cabin split is initially imposed on the passengers via biasing the attractiveness of each exit (see Figure 77). All other model parameters are similar to Scenario 3(a).

Table 48: Model settings for Scenario 3(b) (Additional features are underlined)

Non-fire emergency conditions using the new models	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses non-fire emergency Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ TDIS vision representation, i.e. perfect ✓ PERFECT decisions Parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • Real emergency mode (-1 Drive) • Fixed exit flow rates (see Table 38) • ONE CREW MEMBER • Explicitly modelled	Passenger Objective: ✓ Try to reduce their personal evacuation time via exit selection ✓ Passenger GENERALLY do as instructed ✓ Vision is limited by: ❑ The geometry

As the evacuation progressed passengers began to experience delays and begun to assess the evacuation efficiency for themselves making their own exit choice decisions. This led to passengers quickly deciding upon a nearest exit use pattern.

As the evacuation progressed the crewmember began to redirect passengers in the forward cabin section away from the R2 exit and towards the R1 exit (see Figure 83). Once the forward zone was completely empty the crew bypassed a few passengers forwards to the idle R1 exit in a similar manner to Scenario 2 (see Figure 84). In this scenario the cabin crew attempted to enforce a more optimal movement pattern onto the passengers in the forward and mid-section cabin.

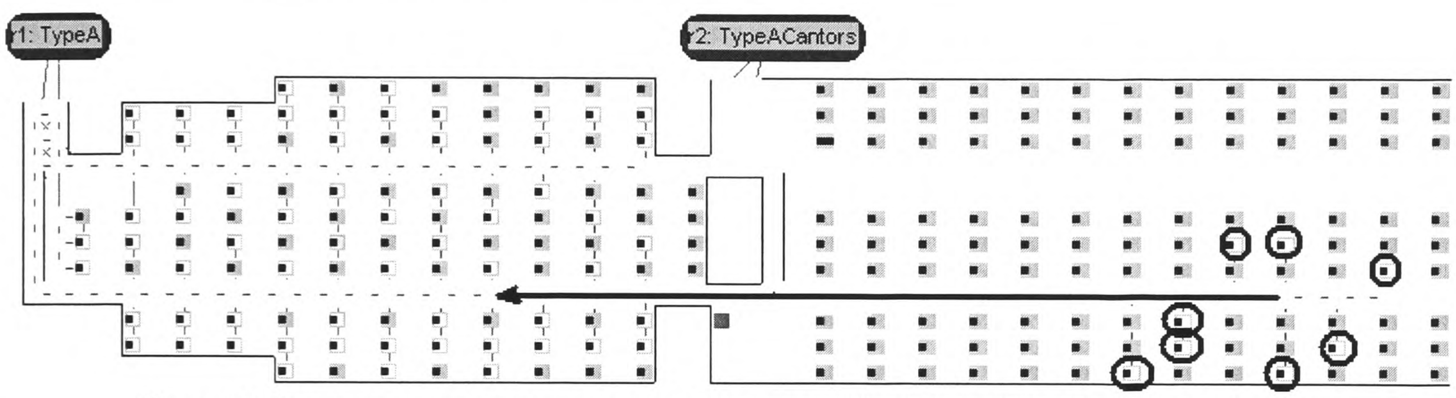


Figure 83: Passengers that the cabin crew bypassed past the R2 and R3 exits in Scenario 3(b)

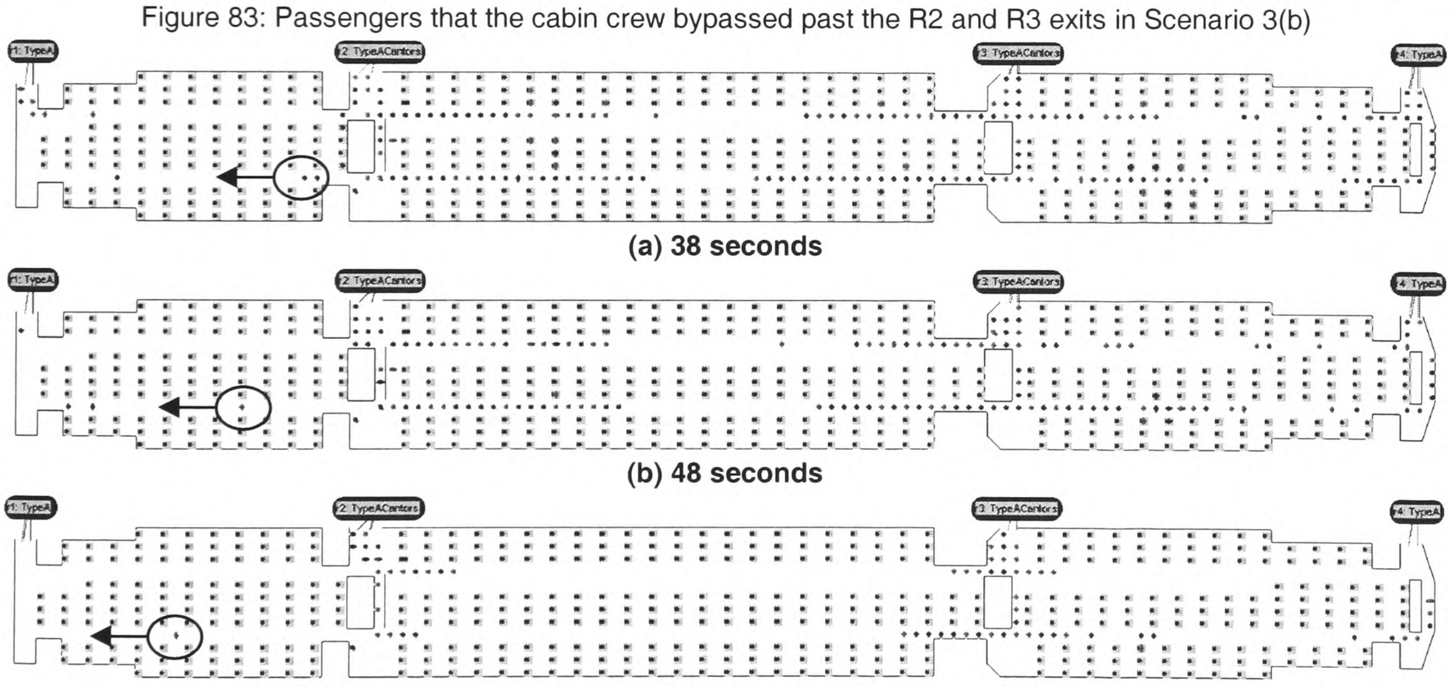


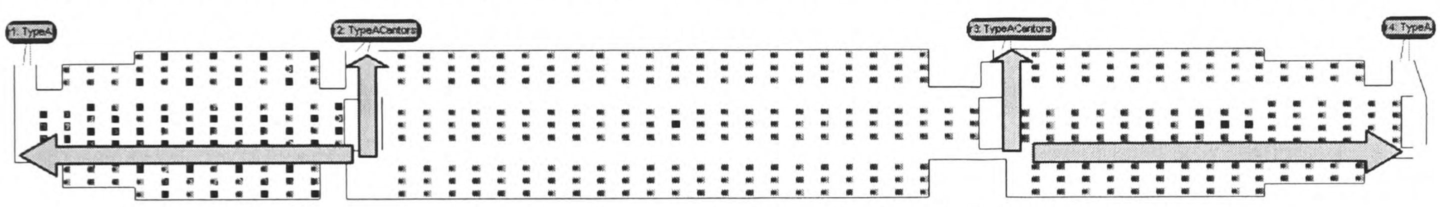
Figure 84: airEXODUS output from Scenario 3(b) showing bypass through the forward cabin section (circled with arrows)

This scenario generated a TET of 82 seconds and an average OPS score of 0.16 (see Table 47

Table 47). The average result of the single crew in this scenario is a reduction in the average evacuation time by 5.6 seconds (6.4%) from Scenario 3(a). In addition the average PET of the passengers reduces from 40.8 seconds to 38.8 seconds. In this scenario the single cabin crew is able to have a significant impact on the efficiency of the evacuation in the forward cabin section. Through the inclusion of a single crew exit use is a little more balanced with 254/400 passengers (63.5%) using the mid-section exits. In the previous scenario without crew 285/400 passengers (71.5%) used the mid-section exits.

6.2.1.6 Scenario 3(c): an evacuation in non-fire emergency conditions with TWO crew making perfect decisions and having perfect knowledge using the passenger exit choice model

In Scenario 3(c) the sensitivity of this aircraft to the number of cabin crew is investigated through the modelling of an extra crewmember in the L3 exit area (see Figure 85). The additional crew has been given responsibility for redirecting passengers between the R3 and R4 exits (see Figure 85(b)). Apart from the additional crew the model settings are identical to those in Scenario 3(b) (see Table 49). For simplicity cabin crew are not placed in the vestibule areas of the L1 and L2 exits.



(a) – two crew, one in the L2 exit area and one in the L3 exit area

Figure 85: Crew bypass locations in the wide-bodied used from scenarios 3(c)

Table 49: Model settings for Scenario 3(c) (Additional features are underlined)

Non-fire emergency conditions using the new models	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses non-fire emergency Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ TDIS vision representation, i.e. perfect ✓ PERFECT decisions Parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • Real emergency mode (-1 Drive) • Fixed exit flow rates (see Table 38) • TWO CREW MEMBERS • Explicitly modelled	Passenger Objective: ✓ Try to reduce their personal evacuation time via exit selection ✓ Passengers GENERALLY do as instructed ✓ Vision is limited by: ❑ The geometry

As in the previous scenario as the evacuation unfolds passengers quickly form their own exit choices that generally involve them using the nearest exit. In this scenario the behaviour in the forward and mid zones is similar to that of Scenario 3(b) and so will not be described again here. The behaviour in the aft seating zone is however quite different and requires explanation.

The crew immediately ascertains that too many passengers in the aft zone are attempting to use the R3 exit and so begins issuing orders for passengers to redirect to the R4 exit. Since the density within the cabin is high she is only able to effectively communicate with relatively nearby passengers. Thus, she cannot communicate with the periphery of the R3 exit queue. Despite this she redirects some passengers aft from the mid portion of the queue (see small arrows with squares in Figure 87(a)). These passengers turn and begin moving against the flow to the R3 exit. As time progresses she is successful at persuading more passengers to turn around (see small arrows with squares in Figure 87(b) and Figure 87(c)).

As increasing numbers begin to move against the flow to the R3 exit the passengers at the periphery of the queue begin to reassess their exit choice in light of the evolving situation in the queue. They spot the high levels of confluence that exists over their initial route and begin to redirect themselves towards the R4 exit. It should be noted that the behaviour whereby passengers turn around in the face of confluences was not explicitly designed, however through the logic of the model this behaviour emerges.

It is interesting to note that the movement pattern begins with passengers using their nearest exit as in Scenario 3(a)), however by the end of the evacuation the crew have enforced a different movement pattern that is similar to the optimal pattern imposed on the certification trial, i.e. Scenario 2 (see Figure 77)). Furthermore in this scenario passengers from the mid-section are bypassed by the crew in both directions (see Figure 86).

The results of Scenario 3(c) is an average TET of 81.8 and an average OPS of 0.15. The average TET has therefore reduced by 6.2 seconds (7.1%) when compared with no crew redirection but only 0.2 seconds (0.2%) when compared with a single crew performing redirection. In these simulations the cabin crew in the aft of the cabin has little effect on the overall evacuation time for the aircraft. However, in this scenario on average 231/400 passengers (57.7%) used the mid-section exits compared with 254/400 passengers (63.5%) when once crewmember was present and 285/400 passengers (71.5%) with no crewmembers. Thus, whilst the TET has not been greatly affected by the second crewmember performing redirection duties the exit utilisation is more balanced.

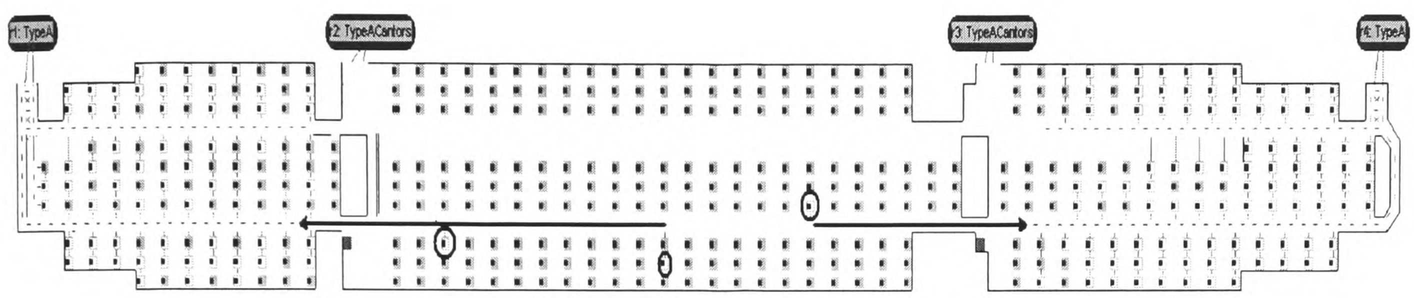


Figure 86: Passengers that the cabin crew bypassed past the R2 and R3 exits in Scenario 3(c)

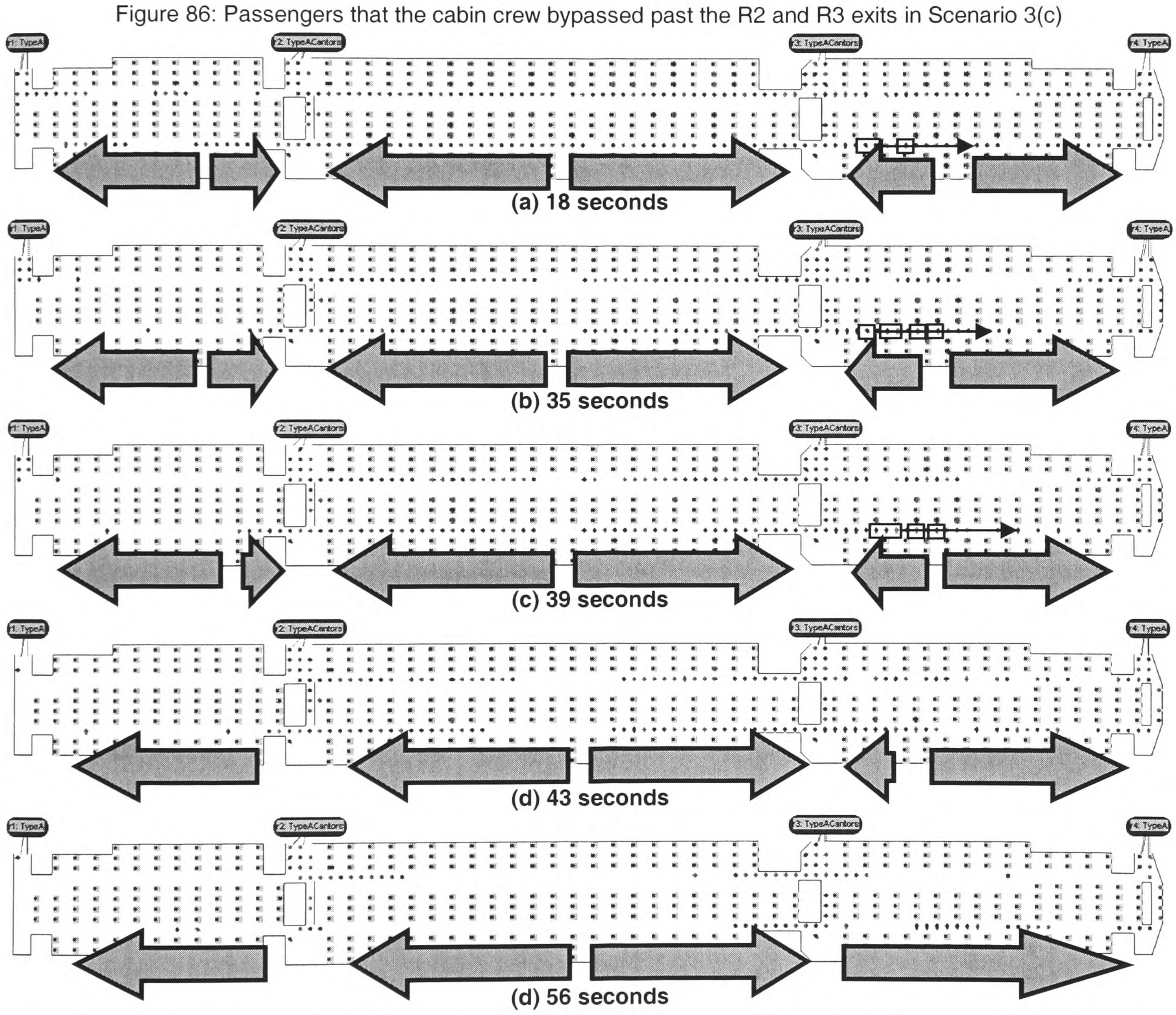


Figure 87: airEXODUS graphic output – Solid arrows indicate general movement trends and small arrows indicate some of the redirection events

6.2.1.7 Scenario 3(d): An evacuation in non-fire emergency conditions with TWO crew making imperfect decisions and having imperfect knowledge using the passenger exit choice model

This section maintains the configuration used in Scenario 3(c) however it limits visibility and uses the crew fallibility model. The visibility from each redirection station can be seen in Figure 88. The regions were manually created and designed to approximate line of sight from each crews' redirection station. The visible area of the cabin will be limited to that shown in Figure 88. In addition crew fallibility is defined such that the crew make errors. A summary of the model settings can be seen in Table 50.

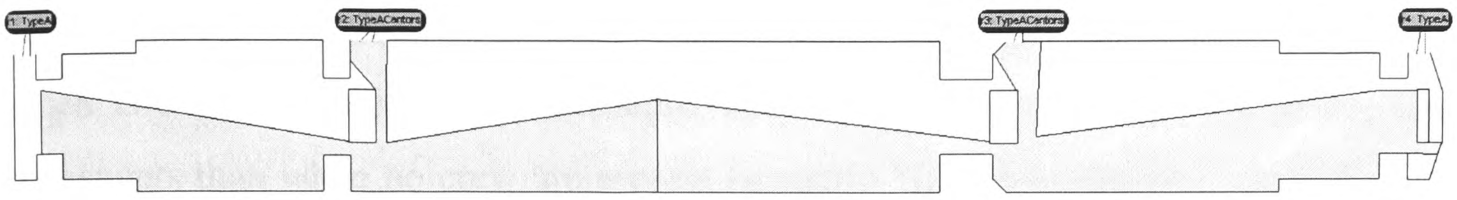


Figure 88: Approximate line of sight visibility given to each crew in Scenario 4(a)

Table 50: Model settings for Scenario 4(a) (Additional features are underlined)

Non-fire emergency conditions using the new models	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses non-fire emergency Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ <u>LOSIS vision representation, i.e. imperfect</u> ✓ <u>IMPERFECT decisions</u> Parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • <u>Local error 4%, Distant error 8%</u> • Real emergency mode (-1 Drive) • Fixed exit flow rates (see Table 38) • TWO CREW MEMBERS • Explicitly modelled	Passenger Objective: ✓ Try to reduce their personal evacuation time via exit selection ✓ Passengers GENERALLY do as instructed ✓ Vision is limited by: ❑ The geometry

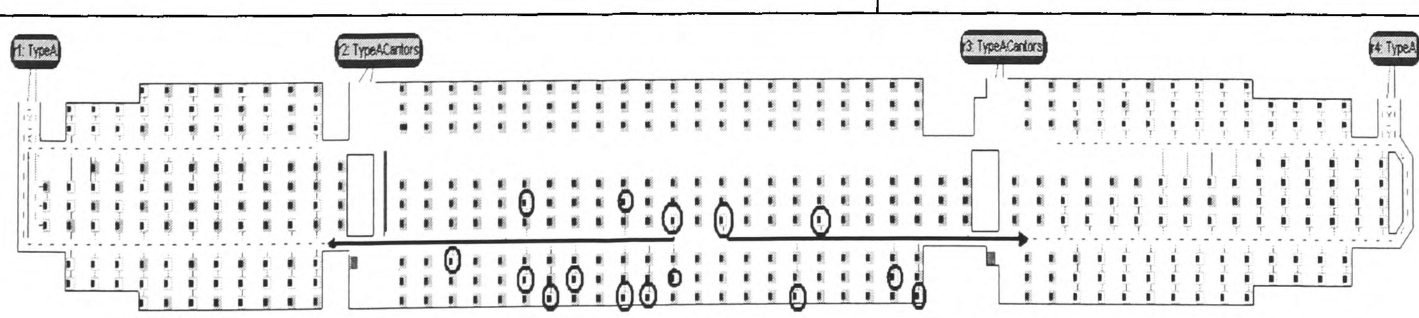


Figure 89: Passengers that the cabin crew bypassed past the R2 and R3 exits in Scenario 3(d)

In this scenario the crew make some poor decisions and bypass passengers that should not 'optimally' have been bypassed and fail to recognise the need to bypass some passengers that should have been. The circled passengers in Figure 89 are passengers that bypassed their nearest exits as a result of crew instructions. The effect of activating the cabin crew fallibility and LOSIS vision algorithms is that the average evacuation time increased to 85.2 second – an increase of 5.7 seconds (7.1%) when compared with an optimal crew performance. It should be noted that the average TET is still lower than the average TET when no crew were redirecting, i.e. an average TET of 87.6 seconds in scenario 3(a). Furthermore the average PET of passengers is still lower when two crew making poor decisions and with limited visibility are redirecting passengers than when no crew are present (scenario 3(a) generated an average PET of 40.8 seconds). Comparing the number of users of the mid-section exits (R2 or R3) shows that on average 250/400 passengers (62.5%) used either the R2 or R3 exits. With an optimal crew performance (i.e. Scenario 3(c)) 231/400 passengers (57.7%) used either the R2 or R3 exits. The introduction of crew fallibility and more realistic vision has led to less efficiency when redirecting passengers away from the oversubscribed R2 and R3 exits.

Table 51: Results for scenarios3(c) and 3(d)

		TET (secs)	PET (secs)	Evacuees (passengers)				OPS
Scenario 3(c) Emergency evacuation With two cabin management crew making perfect decisions	Min	70.6	37.4	54	116	117	86	0.02
	Mean	79.5	38.7	58	122	126	94	0.14
	Max	93.5	40.3	63	129	132	102	0.26
	STD	5.16	0.57	1.60	2.10	3.42	3.35	0.05
Scenario 3(d) Emergency evacuation With two cabin management crew using LOSIS + Errors	Min	76.6	37.5	53	113	122	84	0.07
	Mean	85.2	38.9	59	121	129	90	0.18
	Max	106.2	40.6	67	129	137	96	0.31
	STD	6.68	0.65	3.28	3.30	3.06	2.62	0.05

6.2.1.8 Scenario 4(a): An evacuation in severe fire emergency conditions using the passenger exit choice model with two crew making imperfect decisions and having imperfect knowledge

This scenario investigates the performance of Scenario 3(d) under severe fire conditions. To enable a direct comparison with the results of Scenario 3(d) fire, smoke, etc. has not been modelled, but only the psychological impact of the fire scenario. This limits reductions in travel speeds and deaths due to fire and or smoke and will allow a more direct comparison with the results of Scenario 3(d).

In this scenario the crew were less able to enforce their wishes on the passengers (see iTable 53). As such passengers generally did as they wanted and continued to use their nearest exits. It is interesting to contrast the results of Scenario 4 and Scenario 3(d). In Scenario 3(d) the crew were relatively successful at managing passengers and persuading passengers away from the over utilised R2 and R3 exits. In this scenario the crew have not been as successful at this task. In Scenario 4(a), 282/400 passengers

(71%) used either the R2 or R3 exits whereas in the same Scenario but in non-fire emergency conditions (Scenario 3(d)) the number of users was 250/400 passengers (62.5%). This increase in the number of passengers that used the R2 and R3 results from the crew being less able to enforce their will on passengers and to enforce redirection commands in severe fire conditions. In addition the average TET has increased by 3 seconds (3.5%) when compared against Scenario 3(d). This increase results from the crew being unable to optimise the evacuation as efficiently in severe emergency conditions.

Table 52: Model settings for Scenario 4(b) (Additional features are underlined)

Severe emergency evacuation conditions	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses non-fire emergency Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ LOSIS vision representation, i.e. imperfect ✓ IMPERFECT decisions Parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • Local error 4%, Distant error 8% • Severe emergency mode (-8 Drive) • Fixed exit flow rates (see Table 38) • TWO CREW MEMBERS • Explicitly modelled	Passenger Objective: ✓ Try to reduce their personal evacuation time via exit selection ✓ Passenger GENERALLY do as they want ✓ Non-nearest exit use ❑ 5.6% ✓ Vision is limited by: ❑ The geometry

Table 53: Results for scenarios 4(a) and 4(b)

		TET (secs)	PET (secs)	Evacuees (passengers)				OPS
Scenario 3(d) Emergency evacuation With two cabin management crew using LOSIS + Errors	Min	76.6	37.5	53.0	113.0	122.0	84.0	0.07
	Mean	85.2	38.9	59.5	121.1	129.4	90.0	0.18
	Max	106.2	40.6	67.0	129.0	137.0	96.0	0.31
	STD	6.7	0.6	3.3	3.3	3.1	2.6	0.05
Scenario 4(a) Emergency evacuation With two cabin management crew using LOSIS + Errors (WITHOUT SMOKE and FIRE)	Min	82.4	24.2	40.0	127.0	141.0	70.0	0.09
	Mean	88.5	25.8	43.9	133.9	147.9	74.2	0.20
	Max	107.4	27.6	48.0	141.0	156.0	79.0	0.37
	STD	3.8	0.7	1.8	2.6	2.9	2.0	0.06
Scenario 4(b) Emergency evacuation With two cabin management crew using LOSIS + Errors (WITH SMOKE and FIRE)	Min	86.9	40.5	37.0	135.0	154.0	61.0	0.28
	Mean	93.7	41.9	39.6	139.2	156.8	64.4	0.36
	Max	100.4	43.9	43.0	142.0	161.0	67.0	0.46
	STD	2.8	0.7	1.4	1.5	1.4	1.3	0.05

6.2.1.9 Scenario 4(b): An evacuation in severe fire emergency conditions using the passenger exit choice model with two crew making imperfect decisions and having imperfect knowledge

The final scenario investigates the performance of Scenario 3(d) under severe fire conditions with a uniform smoke atmosphere set to an extinction coefficient of 0.5. Within the model this will give passengers and crew a visual range of 4 metres when viewing other passengers and 10 metres when viewing exit signs (see Section 6.1.2.2 and Figure 90). Apart from the presence of smoke the model settings are identical to those used in Scenario 4(a)

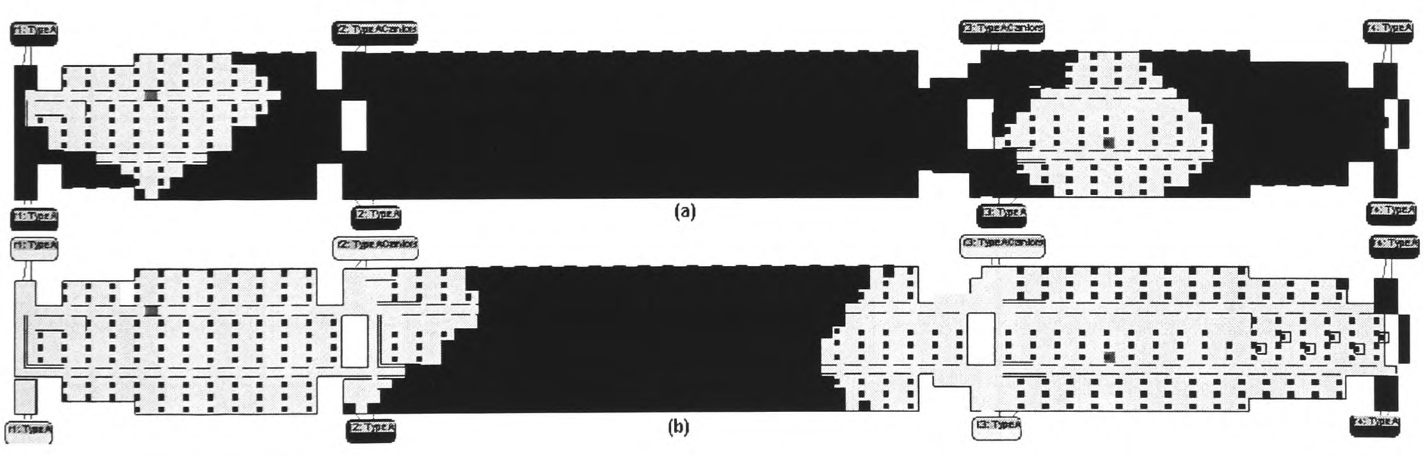


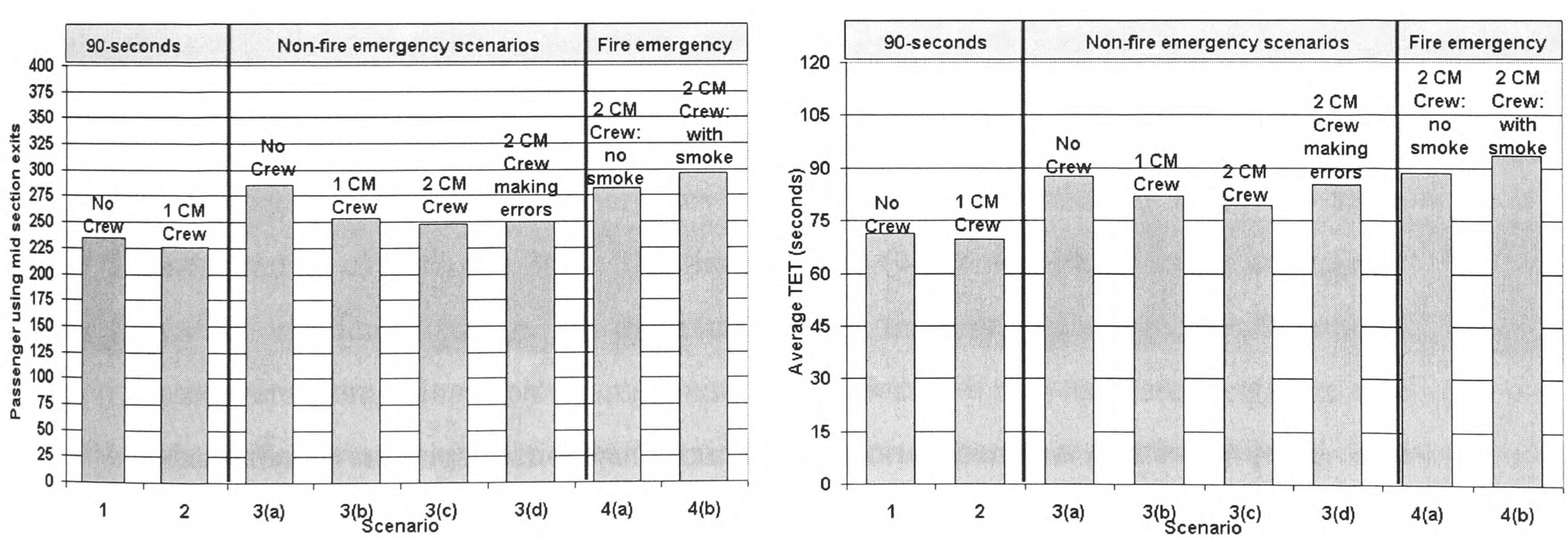
Figure 90: Example output from prototype airEXODUS showing (a) the visual range of exit signs and (b) other passengers in Scenario 4(d)

In this scenario the average TET increases by 5.2 seconds (6%) when compared against Scenario 4(a). In addition the number of passengers that used either the R2 or R3 exits increases from 250/400 passengers (62.5%) in Scenario 4(a) to 296/400 passengers (75%). In these simulations the crew are unable to see all the way to alternative exits and as such attempt to redirect passengers to their local exits only, i.e. the R2 and R3. The increased TET and increased number of passengers using the R2 and R3 exits results in part from the crew redirection in these simulations. In addition, not all passengers can see alternative exits and those that can act on incomplete information sets and were more likely to make, what were with hindsight, poor redirection decisions. The net result of these two factors is a nearest exit usage pattern - this finding correlates well with the findings in Chapter 5 for these types of scenarios.

6.2.1.10 Summary of results

A feature of the aircraft configuration under examination was that some form of redirection of passengers away from mid-section exits towards the R1 and R4 exits was beneficial to the evacuation time of the aircraft as a whole.

To demonstrate this under optimal conditions two 90-second certification trial scenarios were demonstrated. The first (Scenario 1) involved no cabin crew whilst the second (Scenario 2) used the models developed in this work to explicitly model a single crew member in the L2 exit vestibule with responsibility for balancing use of the R1 and R2 exits. In Scenario 2 the crew was able to bypass many passenger forwards from the R2 towards the R1. This resulted in, on average, less passengers using mid-section exits (see Scenarios 1 and 2 in Figure 91(a)) and consequently lower TETs (see Scenarios 1 and 2 Figure 91(b)).



(a) (b)

Figure 91: airEXODUS generated (a) number of passengers that evacuated via mid-section exits and (b) average TETs for scenarios 1-4

Following this the aircraft evacuation was repeated under non-severe emergency evacuation conditions. Four additional scenarios were modelled the first (Scenario 3(a)) using only the passenger exit choice models and the remaining scenarios (Scenarios 3(b)-3(d)) used both the crew redirection models and passenger exit choice models. The first (Scenario 3(a) involved no crew and saw passengers generally use their nearest exits (see Scenarios 3 in Figure 91(b)). The resulting evacuation was less efficient.

In Scenarios 3(b) a single crew was explicitly modelled in the L2 exit with responsibility for balancing the use of the R1 and R2 exit. In this scenario the crew improved the balance of passengers between the aircraft exits (Scenarios 3(a) and 3(b) Figure 91(a)) which led to decreased evacuation times (see 3(a) and 3(b) in Figure 91(b)). Inserting another cabin crew who was responsible for balancing the use of the R3 and R4 exit in the vestibule of the L3 exit demonstrated better exit balancing and reduced TET for the aircraft than with just one crew or no crew (see Scenarios 3(a)-3(c) in Figure 91).

The impact of a decreased crew performance was then assessed in Scenario 3(d) using the LOSIS visual information gathering scheme and crew fallibility models with the same configuration used in Scenario 3(c). This scenario demonstrated a decrease in the crews' ability to manage the evacuation when compared against Scenario 3(c) – an optimal crew performance. However, the results of Scenario 3(d) – 2 crew making errors – were still better than the results of Scenario 3(a) – no crew at all.

Following this two severe emergency scenarios were investigated using the same configuration as Scenario 3(d). The first scenario (4(a)) modelled a severe emergency evacuation without smoke. In these simulations the crew were less able to redirect passengers from using their nearest exits than in Scenario 3(d) as passengers were less subservient to crew instructions and found their shortest personal evacuation route. The result of having the crew (Scenario 4(a)) was however still better than not having them at all (see Scenario 3(a)).

Finally Scenario 4(d) demonstrated a scenario in which a uniform smoke atmosphere was present within the cabin. In this scenario passengers and crew could only see other passengers at a range of 4 metres and exits signs within a range of 10 metres. As such in these models both crew decided against redirecting towards exits they could not see and directed passenger towards their exits only. Some passengers redirected themselves although their decisions were – with hindsight – imperfect. This scenario generated the worst exit balancing and the highest average TETs of any scenarios. In this scenario the crew had a negative impact on the efficiency essentially enforcing a nearest exit use pattern on the aircraft.

To summarise, under 90-second certification trial scenarios the cabin crew redirection models have shown that they can be used to simulate cabin crews' ability to improve evacuation performance and help generate extremely optimal evacuations. The results correlate with the results of real 90-second certification trials. In emergency scenarios the evacuation of this configuration became more problematic as passengers sought their own solutions to their personal evacuation. The passenger exit choice models essentially generated a nearest exit use pattern which the crew had to manage. In non-severe emergency conditions the application of crew member(s) demonstrated better management of the cabin.

In severe emergency evacuation scenarios the passengers were less subservient to the instructions of the cabin crew. The cabin crews' redirection tasks were made much more difficult and rendered less effective. This led to a less efficient evacuation of the aircraft in severe emergency conditions than in non-severe emergency conditions when given the same crew compliment and abilities. This correlates with the analysis presented in Chapter 5. Finally in dense smoke redirection activities of passengers still took place although was undertaken on the basis of reduced information. The crew attempted to redirect all passengers towards their own exit as it was the only exit they could see. These scenarios generated by far the least efficient evacuation of this aircraft.

To conclude, the results of these demonstrations show the sensitivity of the model to the type of scenario, i.e. 90-second certification trial, non-fire real emergency evacuation and severe emergency evacuation involving smoke. In addition, the sensitivity of the models to environmental conditions, the cabin crew numbers and their abilities have been demonstrated. Finally, the overall trends generated by the models correlate well to the findings of Chapter 5.

6.2.2 Full scale narrow bodied model demonstrations

This section demonstrates the model using validation case 5 as a test. Recall from the validation exercise presented in Section 4.5 that some redirection was recommended in order to accurately simulate the evacuation of case 5. Indeed the inability of airEXODUS to simulate crew bypass was cited as an explanation of the 6.4 seconds (10.4%) difference between the airEXODUS results and those of the certification trial. To test this hypothesis the bypass model is employed in this scenario.

6.2.2.1 Narrow Scenario 1: Validation case 5 in 90-seconds certification trial conditions with one crew with perfect knowledge and making perfect decisions

This scenario re-evaluates validation case 5 using the prototype bypass model at the Type-III exit. The basic model is exactly the same as that used in validation case 5 and makes use of the actual data. The only difference in this scenario is that a single cabin crew has been placed at a node directly opposite the Type-III exit. The crew is assumed to be standing on a seat and as such has been given total visual access of the cabin. Note that the cabin of case 5 is relatively open and is not separated by horizontal mid-section partitions. Within the model the crew is given responsibility for the R1 and R2 exits (see Figure 92). Fallibility is turned off at this stage. The model settings for this scenario can be seen in Table 54. These settings represent a best performance for the bypass algorithms.

Table 54: Model settings for Narrow Scenario 1

A 90-seconds certification trial mode using the new models	
Crew features: ✓ Seek to optimise evacuation for aircraft as a whole ✓ Explicit representation of the crew ✓ Assumes responsibility for designated redirection station ✓ Uses 90-second Drive settings ✓ Verbal range determined via functions ✓ Touch range set to 1 metre ✓ TDIS vision representation, i.e. perfect • Crew fallibility not included Parameters: • Crew judgment = 5 second difference • Crew assertiveness = 15 (max) • Fixed exit flow rates (see Table 38)	Passenger Objective: ✓ Always do as instructed

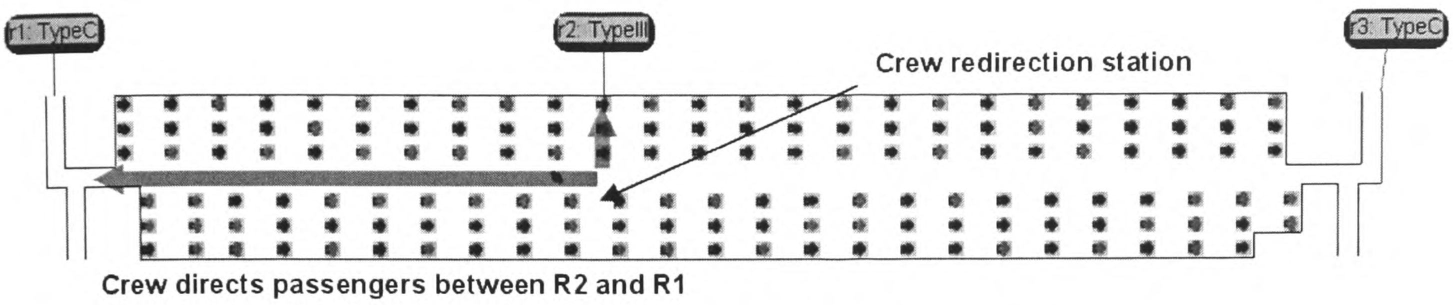


Figure 92: Crew redirection station and responsibilities

From examination of the airEXODUS graphical output is was apparent that during some simulations the crew recognised an imbalance in the likely exit finish times and bypassed a couple of passengers forward to address the imbalance (see Figure 93). In doing so the crew was careful not to starve the Type-III exit and that a flow was maintained to the local exit.

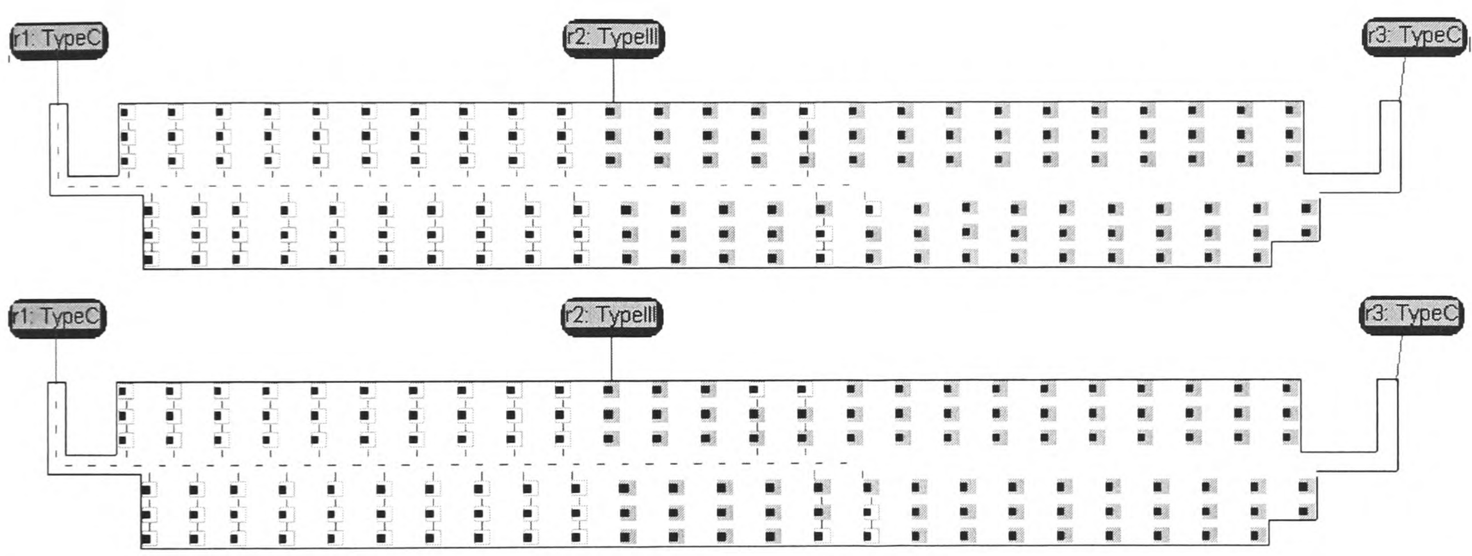


Figure 93: AirEXODUS graphical output showing the exit usage of the R1 exit (R1 users marked in white) in two different simulations of validation case 5 using crew bypass

Table 55: Summary of revisited certification trial case 5 (B737-200)

		TET (secs)	PET (secs)	Evacuees (pax)			OPS
				R1	R2	R3	
Validation Case 5 (BASECASE)	Min	62.9	35.0	60	30	59	0.00
	Mean	70.5	37.8	60	30	59	0.09
	Max	89.8	40.9	60	30	59	0.28
	STD	2.7	0.87	0	0	0	0.04
Validation Case 5 (with BYPASS)	Min	62.5	35.2	59	24	54	0.00
	Mean	69.1	37.4	61.8	31.4	55.8	0.06
	Max	80.7	40.5	68	35	58	0.19
	STD	2.9	0.8	1.6	1.7	0.8	0.04
90-second certification trial		64.1	0.02	60	30	59	0.02

The results of this scenario are contrasted against those of validation case 5 in Table 55. It can be seen that the bypass model has reduced the average TET of the validation case by 1.4 seconds (2%). This reduction is signified by the left shifted frequency distribution of TETs in the bypass scenario (see Figure 94). It is also apparent that the range of TETs is smaller, i.e. the crew is able to avoid some of the lengthy evacuations that occurred in the original validation case. Recall the time recorded during the certification trial of case 5 was 64.1 seconds. The average TET generated when using the bypass model is therefore 5 seconds (7.8%) from the result of the certification trial compared with 6.4 seconds (10%) in the original validation attempt. Furthermore, in the original validation attempt the results of airEXODUS only just captured the result of the certification trial (see Figure 94). When using the bypass model the result of the 90-second certification trial is positioned within the distribution of results generated by airEXODUS (see Figure 94). The bypass model has demonstrated that it is able to improve the performance of validation case 5 and can indeed be used to simulate an evacuation that is optimised via crew flow management procedures.

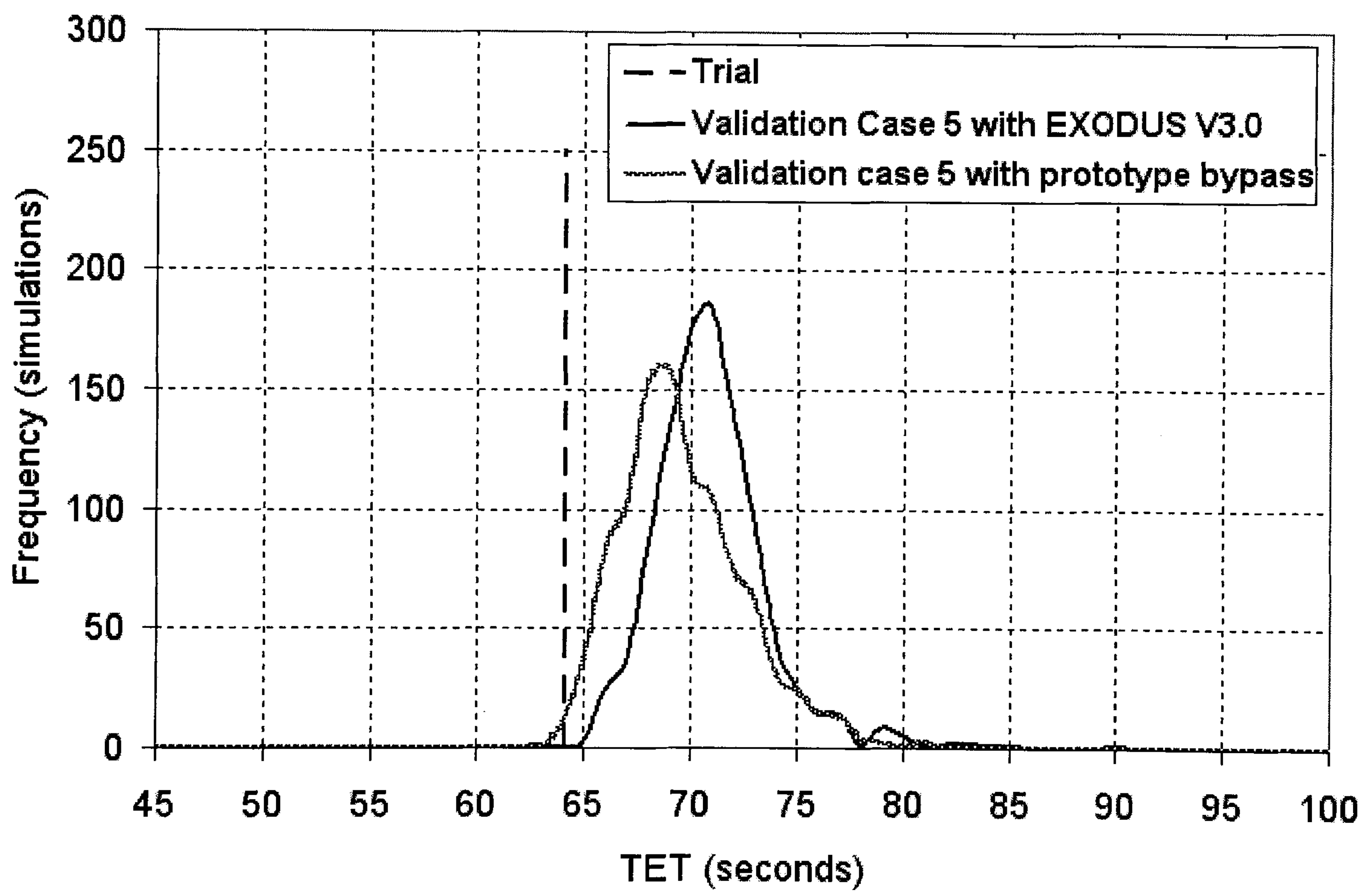


Figure 94: Frequency distribution of TETs generated by airEXODUS in certification trial case 5 using the actual data with and without crew redirection

6.3 Concluding remarks

This chapter has described the development of a model to simulate cabin crew redirection and passenger exit choice in 90-second certification trials, non-fire/external fire scenarios and burn-through/internal fire scenarios. The principle mechanisms that are involved in these behaviours are the collection of information, its processing and then the actioning of any decision based on the above.

Both passengers and crew have been provided with a rudimentary scheme for simulating their information gathering capabilities based on sight, which is affected by both the geometry of the structure and the environmental conditions within the cabin. This scheme allows passengers and crew to make decisions based on the information that they have available to them. Features of the models developed are that the passengers tend to make decisions based on what they perceive as best for them personally, whereas crew make decisions based on what is best for the aircraft as a whole. A method for resolving these sometimes conflicting goals has been developed within this chapter based on the severity of the scenario.

The sensitivity of the models that have been developed is demonstrated through some relatively simple scenarios. These demonstrated that the models are sensitive to the type of evacuation scenario and the number and efficiency of cabin crew. Finally, the previously validated narrow bodied validation case 5 was repeated using the new models. The results generated when using the new models were found to correlate better with the result of its 90-second certification trial than those without the new models.

7 The introduction of passenger route optimisation models

The previous chapter was concerned with how passengers and crew determine overall evacuation strategy through exit choice. This chapter is concerned with the strategies that are employed by passengers en route to their chosen exit. Prototype models that can be used by passengers during their journey to their chosen exit are developed in this chapter. These models represent mechanisms by which passengers can circumvent delays and further optimise their chosen route. This section is concerned primarily with two main route optimisation strategies, they are aisle swapping, and passenger seat climbing.

7.1 When and where these behaviours occur

Aisle swapping in the context of this work is when a passenger swaps to another aisle in order to speed his/her evacuation (see Figure 95). Chapter 5 defined some basic rules that would govern aisle swapping behaviour. This chapter develops the rules into a computer based model that can represent this behaviour in multi-aisle passenger aircraft.

From the analysis of 90-second certification trials it was apparent that aisle swapping occurred relatively frequently in wide-bodied aircraft evacuations (6/9 of wide-bodied aircraft examined had some aisle swapping). However, aisle swapping was not recorded in passenger accounts from real accidents. As mentioned previously this is not thought to indicate that aisle swapping does not occur but may indicate that it is considered an unimportant feature that is not worthy of description in post accident accounts. Indeed, given that it occurs in 90-second certification trials there is no reason to presume that aisle swapping will not occur in real emergency evacuations both with and without fire. The model that is developed therefore applies to 90-second certification trials and real emergencies both with and without fire (see Table 56).

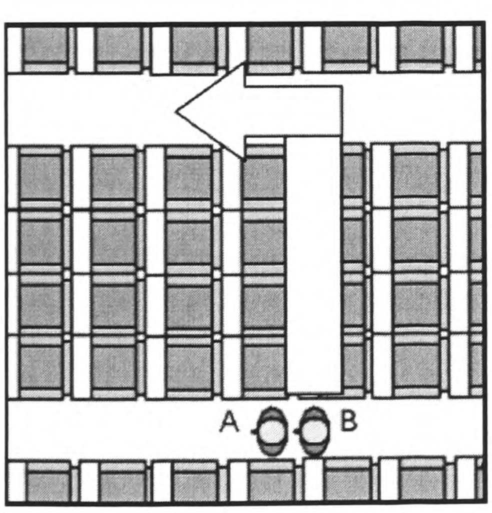


Figure 95: Passenger B is travelling faster than Passenger A and decides to swap to another aisle

In contrast, scrutiny of 90-second certification trial footage indicated practically no instances of seat climbing behaviour. Unlike our knowledge of aisle swapping behaviour in real accidents which was incomplete and based on the transcripts of passengers, we definitely know that seat climbing does not occur during 90-second trials as we have video evidence of the trials. Furthermore, accounts of seat climbing were rare in evacuations that did not involve a severe fire and/or smoke that penetrated the cabin in some way. Given this, seat climbing behaviour will only be considered an option by passengers within the models developed in this chapter in severe emergency evacuations that involve fire. In 90-second certification trials and real accidents that do not involve fire seat climbing will not be considered by passengers, i.e. no model will be developed.

A consequence of the above is that two methods of route optimisation are available in real emergency evacuations and only one in non-fire emergencies and 90-second certification trials (see Table 56). In the case of severe emergencies involving fire a mechanism for both models to operate together is developed at the end of this chapter.

Table 56: Route optimisation stategy by scenario type

Available route optimisation strategies	90-seconds certification trial	Real emergency without fire	Real emergency with fire
Aisle swapping	Yes	Yes	Yes
Seat climbing	No	No	Yes

7.2 A model to represent passenger aisle swapping behaviour in wide-bodied and multi-aisle passenger aircraft

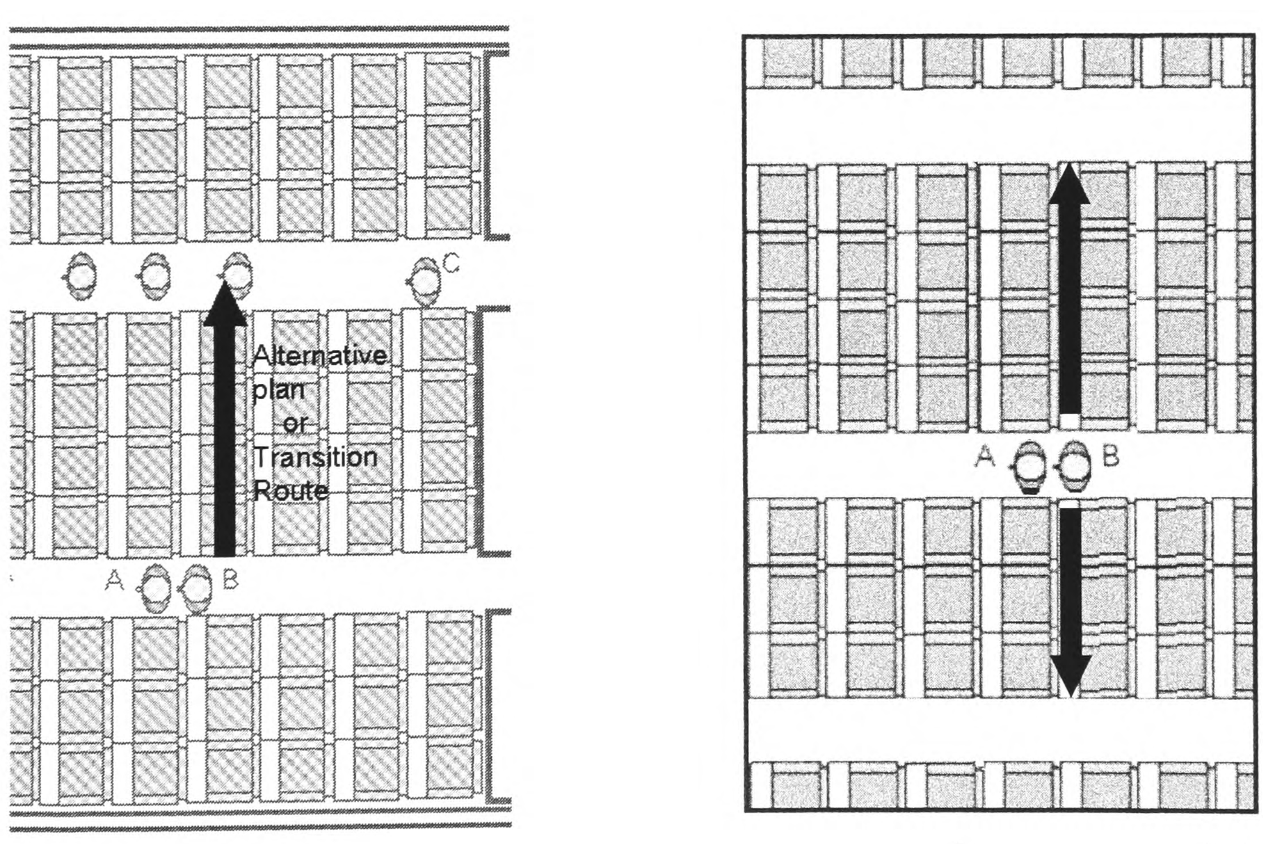
7.2.1 The prototype model

7.2.1.1 Becoming impatient and determining an alternative route to the exit

It is assumed that before a passenger can consider swapping aisles they must first become dissatisfied with their current position. By definition aisle swapping occurs from a position in an aisle. As such, the passengers occupy what is arguably a good position within the cabin, i.e. they are not within seat rows. When aisle swapping occurs the passengers involved are looking to swap a good position for another 'hopefully' better position in a faster moving aisle. Within airEXODUS a patience attribute is assigned to each passenger. Within the aisle swapping model the Patience attribute (typically between 0-10 seconds) is contrasted against the length of delay experienced by a passenger at any given node. Should a delay at a node exceed their patience then they consider aisle swapping behaviour. Should the delay be below their patience then they continue to wait patiently in the queue.

Having become inpatient the next stage in the model is for the passenger to recognise that an alternative aisle is available. A mechanism is therefore required that allows passengers to search for routes to other aisles. Within nodal evacuation models, such as airEXODUS, a route to the alternative aisle can be obtained via treating the mesh of nodes as a graph. This is advantageous as graph theory literature contains numerous methods for finding shortest paths through graphs. One such method is applied in this model. From the various available methods, the Best-First graph search algorithm was employed [164]. This algorithm is widely used today and so will not be mentioned here. Suffice to say that the time taken by a passenger to traverse connecting arcs was used for the heuristic of each arc.

Using an exhaustive Best-First graph search algorithm a list of available routes to alternative aisles is generated. The first path in the list represents the shortest route to an alternative aisle. Within the model the routes to the alternative aisle(s) are referred to as the passenger's planned alternative route(s), or transition route(s) (see Figure 95).



(a) (b)

Figure 96; Example transition routes on (a) a wide-bodied aircraft and (b) a multi-aisle aircraft

Once the passenger has ascertained that an alternative route exists the next stage of the model involves the passenger determining if any of the alternative routes and associated aisles yield any perceived benefit to the speed of their evacuation. A method of determining this is now developed. The method presented is primarily based on observations from 90-second certification trial video footage.

7.2.1.2 Ascertaining the merit of an alternative aisle

A conclusion of the analysis of video footage was that generally passengers only swap aisles when there is space in the adjacent aisle(s). Thus, the first assessment of the merit of alternative routes is for the passenger to make a determination of whether there is sufficient space in the adjacent aisle.

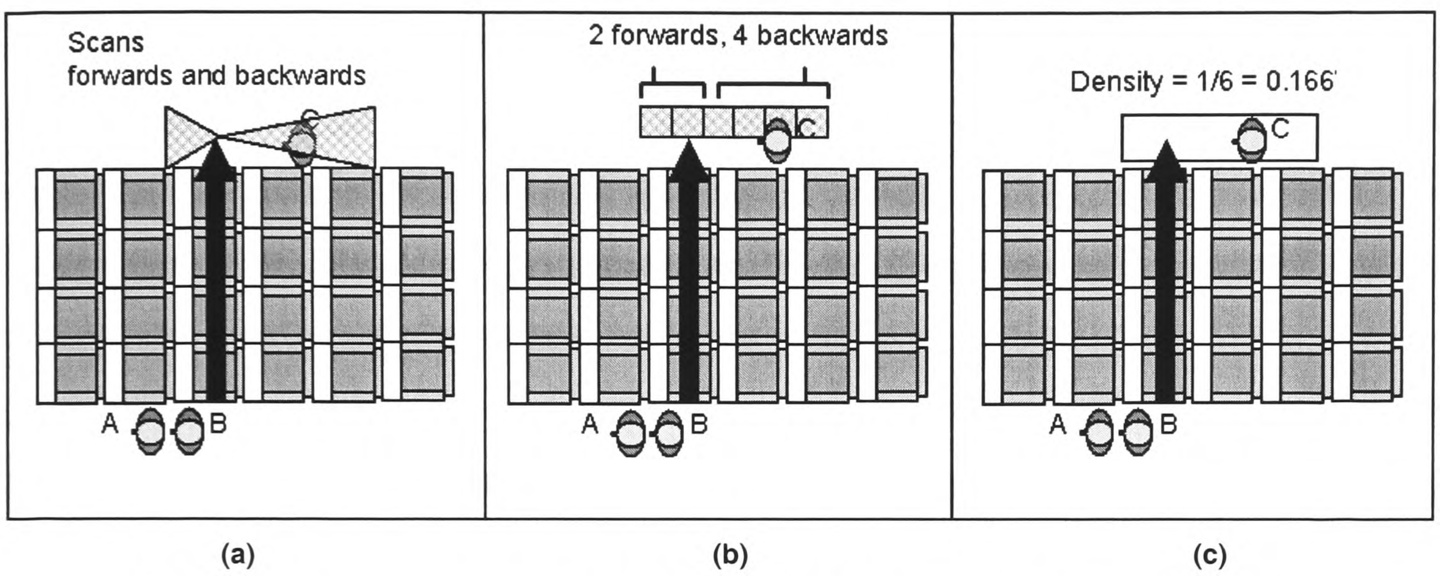


Figure 97: Passenger examines the density at the discharge of the transition route

Within the model a passenger will scan forwards and backwards from the proposed discharge of the aisle (see Figure 97(a)) in order to ascertain if the region into which they will move is relatively free from other passengers. As mentioned previously, there are no definitive accounts of passengers describing their rationale for aisle swapping. Thus, the determination of what constitutes a suitably low density for a passenger to consider swapping aisles is somewhat arbitrary.

At this stage in the model the passenger is simply assessing whether there is a relatively unimpeded route into another aisle. Mechansims are provided for passengers to assess conditions in the aisle ahead of their discharge point. Within the model passengers scan a small area forwards and a larger area backwards from the discharge point. This is because passengers would be concerned that those behind them would intersect their path. Furthermore, observations from 90-second certification trials suggest that a scheme that ensures that passengers swap to areas near the back of queues is important (see Section 5.3.4). Having passengers assess a greater area backward of the transition discharge would help to ensure these two aspects. An arbitrary range of 2 nodes forwards and 4 nodes backwards is proposed within this model when determining if there is space to swap aisles (see Figure 97(b)). It should be noted that this approach will not prohibit passengers from swapping into the mid-portion of queues should sufficient space be available.

To mimic the observations of 90-second certification trials two density settings were implemented. The first setting applies only to the first passenger to aisle swap from an aisle and requires the adjacent area to be completely empty, i.e. a density of zero passengers/metre. The second setting applies to passengers that are in an aisle that has already been either the recipient or originator of an aisle swapping passenger. Under these circumstance the requirement is that the area is less than half full, i.e. a density of less than 0.5 passengers/metre. Whilst rather arbitrary, this scheme reflects the observations from 90-second certification trials and generates behaviour such that an initial aisle swap is rarer than subsequent aisle swaps.

It is obvious that in some circumstances swapping aisles would be more advantageous than others. For example, a passenger being stuck behind a highly disabled passenger some distance from the exit whilst an alternative aisle is completely empty would present a very different aisle-swapping scenario to that of a passenger being stuck behind one or two fast moving passengers again with an empty opposite aisle but only being 4 metres from an active exit. Thus, passengers need to be provided with a method of assessing the 'merit' of aisle swapping. Essentially this will involve an assessment of the speed that other aisles are moving and the likely time it would take to reach the exit should the alternative routes be taken.

Numerous methods of determining the merit of swapping aisles exist such as counting the number of people in the aisles, estimating a flow rate for the aisle, determining the speed of aisle users, to name but a few. Each of these methods have their advantages and disadvantages. For example, simply counting the number of users in the aisle would allow a determination based on reducing the possible points of congestion however it takes no account of the current flow in the aisle. Calculating a flow rate for the aisle would allow the passenger to gain a crude estimate of the likely finish time of the aisle, however a flow rate represents an average over time, not the current performance level of the aisle flow.

A finding of a later section is that sub-queue congestion develops behind slow moving passengers (see Section 8.2 and [36]). This results from the passenger only being able to move as fast as the slowest person in front of them. This notion offers an alternative approach to calculating the speed of an aisle. Assuming that there are no delays at the aisle discharge, then the movement rate for any aisle is governed by the speed of the slowest person within that aisle. This observation offers an alternative approach to estimating the current flow conditions within an aisle. However, the success of this approach rests on the assumption that no congestion exists at the discharge of the aisle.

This assumption is not unreasonable as aisle swapping invariably occurs on wide-bodied aircraft, i.e. those that generally have dual lane exits, and the density requirements are generally met once an aisle has begun to exhaust its supply of passengers and the exit is therefore under utilised. Using this method, a passenger can assess the merit of the aisle that he is currently situated within using 30.

$$\mathbf{T_{x,a} = [\ d_{a,x} * \min(S_{a,x}|tr_{p,a})\ ] + t_{x,a} + tr_a} \qquad 30$$

$\mathbf{T_{x,a}}$	=	**the revised time for to reach exit $_x$ using aisle $_a$**
$\mathbf{\min(S_a|tr_a)}$	=	**a list of passenger movement rates that are in aisle $_a$ that lie *en route* to exit $_x$ given a transition time tr_a**
$\mathbf{d_{a,x}}$	=	**the length of the current aisle $_a$ en route to exit $_x$**
$\mathbf{t_{x,a}}$	=	**my travel time through the vestibule area en route to exit $_x$ when using aisle $_a$**
$\mathbf{tr_{p,a}}$	=	**the time required to reach aisle $_a$**

This equation yields an estimate ($\mathbf{T_{x,a}}$) of the time required to reach the exit using an aisle. The measure ($\mathbf{T_{x,a}}$) is calculated as, the time required to reach the vestibule assuming the speed of the slowest person within the aisle under consideration, i.e. Aisle Distance 'A' in Figure 98, and the time required to reach the exit once within the vestibule ($\mathbf{t_{x,a}}$) assuming that the passenger can move unimpeded, i.e. Vestibule Distance 'B' in Figure 98. Optimistically the passenger in this method assumes that he can move unimpeded once he has vacated the aisle, even through cross aisles. This assumption is supported by the fact that cross aisles can be wider than aisles, dual cross aisles may exist and that the passenger may have an opportunity to overtake any slow moving passenger in the vestibule area. Equation 30 includes the time required to traverse the transition through seating ($\mathbf{tr_{p,a}}$).

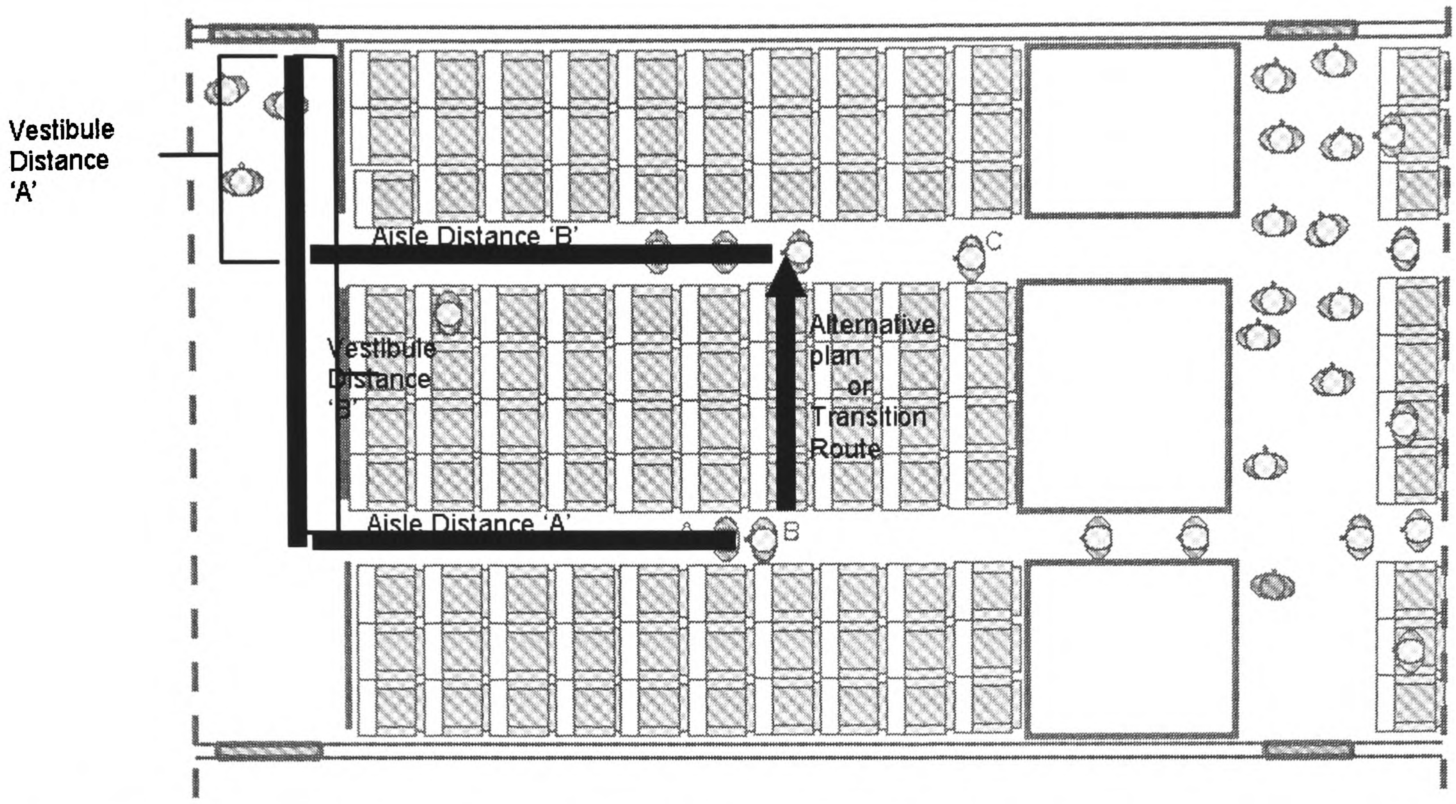


Figure 98: Example of how passenger B would assess the merit of using the current and alternative aisles

A feature of this method is that the transition time is used to determine those passengers that will be ahead of the passenger once the transition has been completed. This is important as a slow moving passenger could sneak in front of the transitioning passenger thus losing any calculated benefit. In order to avoid this, when determining the slowest moving passenger in the proposed aisle the passenger uses the estimate of the transition time to look backwards from the transition discharge. Within the model passengers who will reach the transition discharge during the transitioning period are included in the assessment of the slowest moving passenger within the alternative aisle. Thus, if a slow moving passenger will have moved in front of the passenger during the transition, then its impact upon the estimate is considered (see Figure 99). The equation can be used to ascertain the merit of using any aisle within the model, including the current aisle, if $\mathbf{tr}_{p,a}= 0$ then the aisle under consideration is the current aisles, if $\mathbf{tr}_{p,a}\neq 0$ then the aisle under consideration is not the passengers current aisle. Thus Equation 30 can be used to determine the merit of all of the aisles that are available including the current aisle.

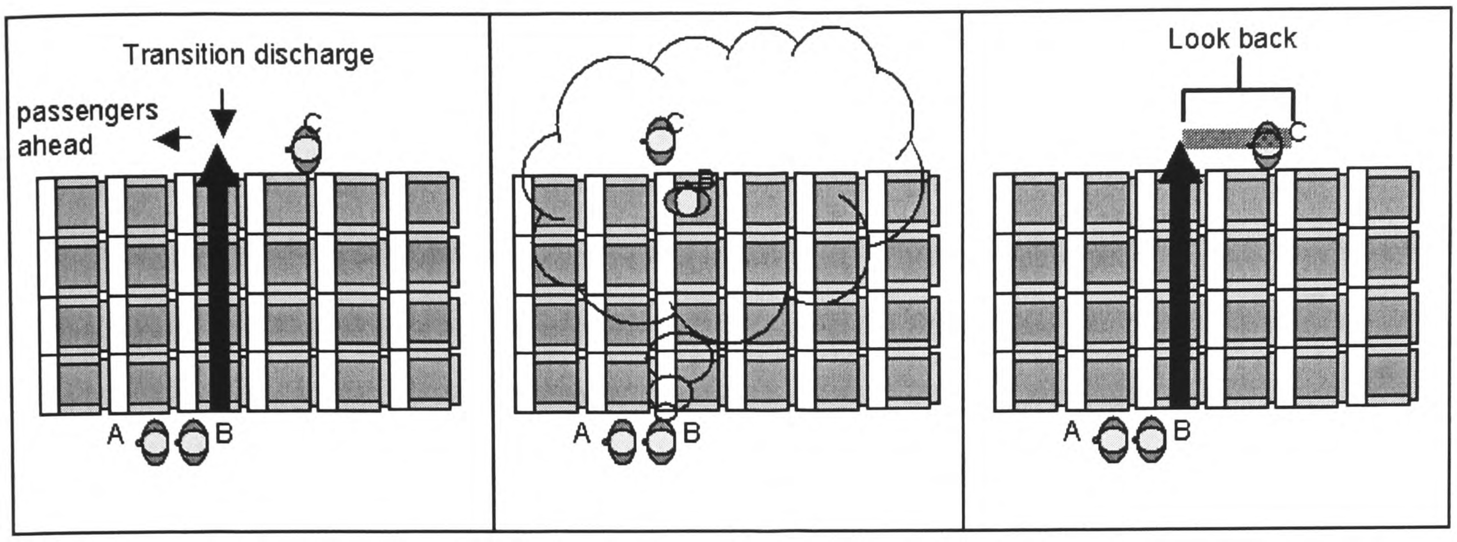


Figure 99: When considering the speed of the alternative route passenger B should consider those passengers that would be intersect his path whilst he is crossing the transition route

Applying Equation 30 to all of the aisles that are available indicates the aisle that represents the best option. Given the mathematical nature of this assessment, an alternative aisle could represent a better option than the current aisle by minuscule amounts, such as 0.1 seconds, 0.001 seconds, etc. As with the passenger exit choice model this level of judgement is simply unrealistic and must be removed. Thus the same minimum threshold for passenger observation (5 seconds) that was used in the passenger exit choice model is also employed in this model. Passengers will only detect a difference in evacuation times that are greater than the threshold value, i.e. when the absolute value of $[T_{x,\text{current aisle}} - T_{x,\text{best aisle}}] > 5$ seconds.

7.2.1.3 Incorporating a probability value for aisle swapping

An observation from scrutinising videos of 90-second certifications was that in some instances when an opportunity to aisle swap was available it was not necessarily used (see Section 5.3.3). The video footage of 90-second certification trials demonstrated that aisle swapping events were not exclusively triggered by physical conditions within the cabin. Indeed other factors influenced the decisions of passengers, such as a reluctance to be the first to take a new type of action or whether others supported your view by swapping aisles in the cabin section. The video evidence suggests that it is more difficult to be the first person to take the decision to aisle swap when presented with an oppourtunity than to swap aisles once others have done so. Indeed until aisle swapping events occur, most passengers exposed to aisle swapping conditions choose to stay in their current aisle. However, once aisle swapping has occurred the initial difficulty / reluctance dissipates and numerous passengers may then decide to aisle swap. It could be that this behaviour is imposed by the nature of the 90-second certification trial methodology, rather than being a genuine behaviour that would be witnessed in real emergency evacuations. However, there is no evidence to support this argument and it is therefore purely conjecture. Whatever the reason, there are more factors involved in determining whether an aisle swapping event will take place than merely analysing the physical conditions. As mentioned previously, the difficulty / reluctance in being the first passenger to aisle swap is partly modelled by requiring that the first passenger to aisle swap has zero density in his assessment region in the adjacent aisle. However, this alone would not generate the behaviour seen in some of the certification trials.

Ideally, we would measure from the video evidence the number that had the opportunity to be the first to swap and the actual number that did. However, given the quality of some of the video footage this would prove extremely difficult. As an alternative to this we know that 4.2% of the total number of passengers in these arircaft actually swapped. If we assume each swapping event is independent of each other, that people only swap aisles once and that our dataset of evacuations represents is representative of certification evacuations. Then the 4.2% figure represents the upper limit on the number of passengers that could have instigated aisle swapping behaviour in certification trials. If we were to use this figure it would most likely represent an overestimate of the total number of passengers that would be prepared to instigate aisle swapping behaviour.

It is therefore suggested that the probability of instigating aisle swapping is set to 0.042. This number could, of course, be edited by the user should data become available in the future. For passengers located in the same aisle or the alternative aisle the probability of aisle swapping is determined only via the aisle swapping algorithm thereafter, i.e. probability of instigating aisle swapping thereafter is 1. This should generate the observable behaviour whereby passengers within the vicinity are more likely to swap aisles following its instigation.

As mentioned previously the presence of a thermo-toxic environment affects passenger psychology and physiology (see Section 5.4.1). An earlier finding of this research was that the type of passenger behaviour various according to the evacuation scenario. In chapter 6 modifications to redirection and bypass behaviour was determined whether the scenario involved a burn through fire or no-fire/external fires. In terms of human behaviour passengers are likely to be marginally more anxious in non-severe real emergency evacuation (for example, those that do involve fire or threat to life) than a 90-second certification trial. However in evacuations that involve smoke inside the cabin and a threat to life, passenger motivation is likely to be increased much further. As such it is recommended that the probability of passengers deciding to instigate aisle swapping is left unchanged in non-fire / external fire scenarios. However, in severe evacuations passengers would be more likely to break with their normal behaviour and consider aisle-swapping behaviour possibly involving seat climbing. In severe evacuations, the emergence of (in the context of 90-second certification trials) seemingly 'abnormal' and somewhat 'extreme' behaviours is clear from the investigation of human behaviour (see Sections 5.4.6 and 5.4.7). From this discussion it was clear that when a fire is present and an entrapment situation is developing passengers are more than willing to consider novel patterns of behaviour that could save their lives. Within the model the probability of passengers instigating aisle swapping behaviour is completely removed in severe evacuation scenarios (those that involve fire for example). This enables passengers to aisle swap when ever they ascertain a benefit can be derived. This would have the affect of making aisle swapping behaviour far more likely in emergencies involving fire. A summary of the various prerequisites to aisle swapping are shown in Table 57.

Finally, the prerequisites that are currently used within the model are uniform for all passengers. In reality passengers would likely have their own prerequisites for aisle swapping. At this stage of model development there is insufficient data to support a more realistic representation of these aspects. Consequently a simplistic approach has been developed.

Table 57: Pre-requisites to aisle swapping according to the scenario type

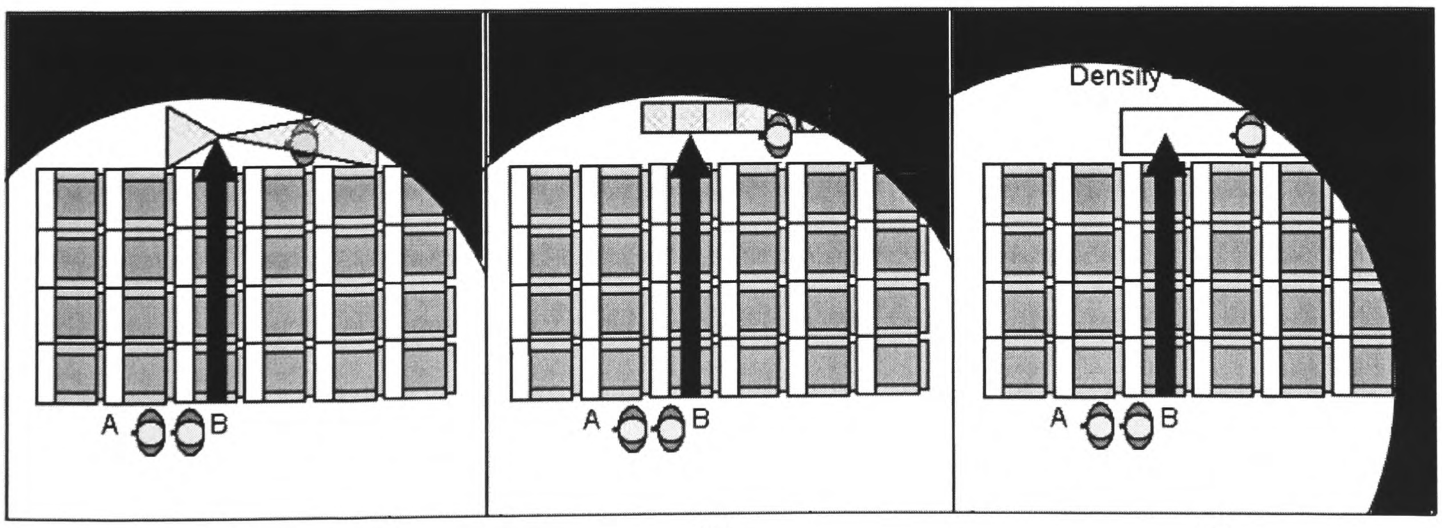
SCENARIO	CONDITIONS THAT MUST BE MET TO CONSIDER AISLE SWAPPING	
	INSTIGATING AISLE SWAPPING WITHIN AN AISLE	SUBSEQUENT TO AISLE SWAP IN SAME AISLE
90-SECONDS	ZERO DENSITY + 0.042 PROBABILITY	<0.5 DENSITY
REAL EMERGENCY	ZERO DENSITY + 0.042 PROBABILITY	<0.5 DENSITY
SEVERE EMERGENCY INVOLVING FIRE	ZERO DENSITY	<0.5 DENSITY

7.2.1.4 Aisle swapping in smoke environments

In addition to affecting the psychology of evacuees smoke also has the capability of reducing passenger visibility. A method of calculating the area that passengers would be able to see during an evacuation involving smoke has been developed as part of this work (see Section 6.1.2.2). The same method is employed within this model to limit the information that passengers have when searching for alternative aisles, determining the density at the discharge of the alternative, witnessing other aisle swapping events, the speed at which the aisle is moving and the distance to the exit.

When searching for alternative aisles the visibility algorithms are used to limit the area that passengers can search. Thus, situations could arise in which a passenger could only assess the merit of only one aisle as visibility of others is completely obscured. It is unlikely that a passenger would even consider an obscured aisle but may possibly consider redirection into another visible aisle.

In addition, visibility of the area in which the density of the alternative aisle is calculated could be reduced (see Figure 100). Should this occur the density is calculated using only the visible nodes. Situations in which nodes are partially obscured (see Figure 100(b)) do not occur as the smoke algorithm operates over discrete nodes.



(a) (b) (c)

Figure 100: Smoke visibility reducing density assessment

The number of passengers whose travel speeds are incorporated into Equation 30 ($\min(S_{a,x}|tr_{p,a})$) could also reduced according to visibility. However, in dense smoke a passenger may be unable to see the slowest moving passenger but would have some intuitive feeling that the current aisle is moving slowly by the length of delays that they are directly experiencing. Should they not directly experience delays, they may still be able to see passengers ahead that are moving slowly and are experiencing direct delays. In this instance the passenger would be able to ascertain some knowledge of the speed of other passengers and, as their movement speeds maybe influenced by those in front of them, some knowledge of the overall speed of the aisle. Before this can be modelled some simplification is required to represent this rather complex method of knowledge acquisition within the model. It is proposed that knowledge of the speed of the aisle is calculated as normal providing that at least a passenger is visible or in the case of complete visual obscuration they are experiencing a direct delay.

With respect to their consideration of alternative aisles it is apparent that their knowledge is dependant upon vision, i.e. they cannot experience a direct delay. However, given that the passenger is able to see some of the passengers in the alternative aisle again he/she would be able to ascertain some knowledge of the queue speed via the speed that the visible passengers are moving. Again their movement speeds may be influenced by those in front of them and the passenger could gain some idea of the movement speed of the aisle from beyond their own vision. As before the rule within the model is that passenger can ascertain the speed of the aisle as normal providing that other passengers in the alternative aisle are visible.

Logically, the above argument would not apply to the backward scan from the transition route discharge (the scan to find slow moving passengers that may intersect their alternative path). Knowledge of this area is only gained through direct sight. Thus, knowledge of this area is reduced according to the smoke algorithms.

Finally, according to the work of Jin [146-148] exit signs are visible at greater distances than passengers. Should a view of the exit not be available the passengers distance assessments ($d_{a,x}$) and travel time estimate through the vestibule area is $t_{x,a}$ is subject to an error of ±25%. Whilst arbitrary the percentage represents the inherent difficulty in judging distances in smoke environments.

The net result of these features is that in very dense smoke conditions the accuracy of passengers' assessment of the merit of swapping aisles is reduced, such that they could make poor decisions. In very dense smoke passengers are unable to see any alternative aisles and consequently would not have the option of swapping aisles at all.

7.2.2 Examples of the aisle swapping models

This section demonstrates numerous different scenarios in which passenger aisle swapping is activated. A hypothetical cabin section was generated for these demonstrations. The cabin section contains 172 passengers arranged in the 2-4-2 configuration (see Figure 101). Pairs of Type-A exits are located at the forward and aft of the cabin section. Each exit is connected to a clear space vestibule area capable of supporting 6 passengers when fully packed. The left and right vestibules are connected via a large cross-aisle wide enough for two passengers to move side by side towards the exit.

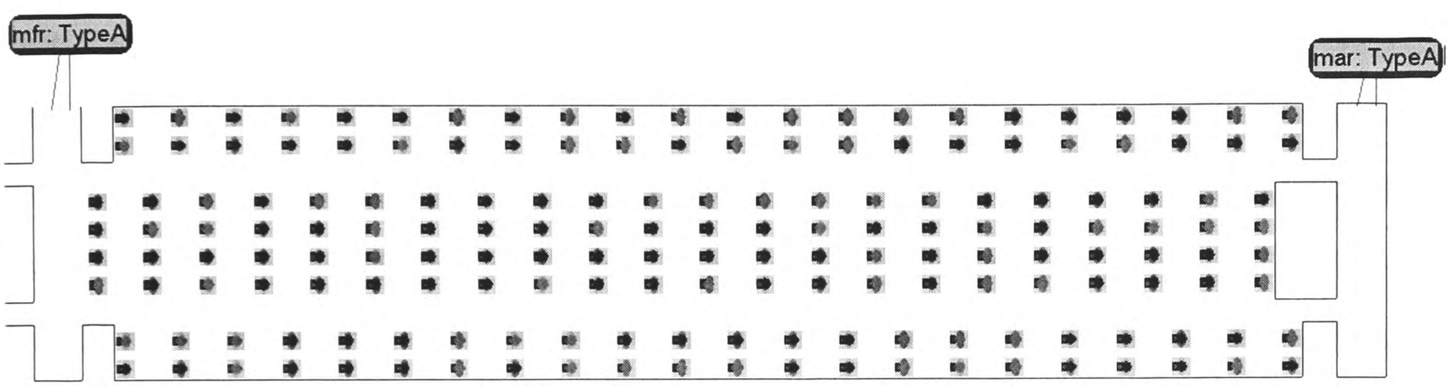


Figure 101: Example of the hypothetical cabin section

In these scenario only the right forward exit (designated as MFR) is active. With the exception of the elderly passenger(s) the population has been defined in accordance with the requirements of FAR Appendix J Evacuation Demonstrations [12].

7.2.2.1 The scenarios

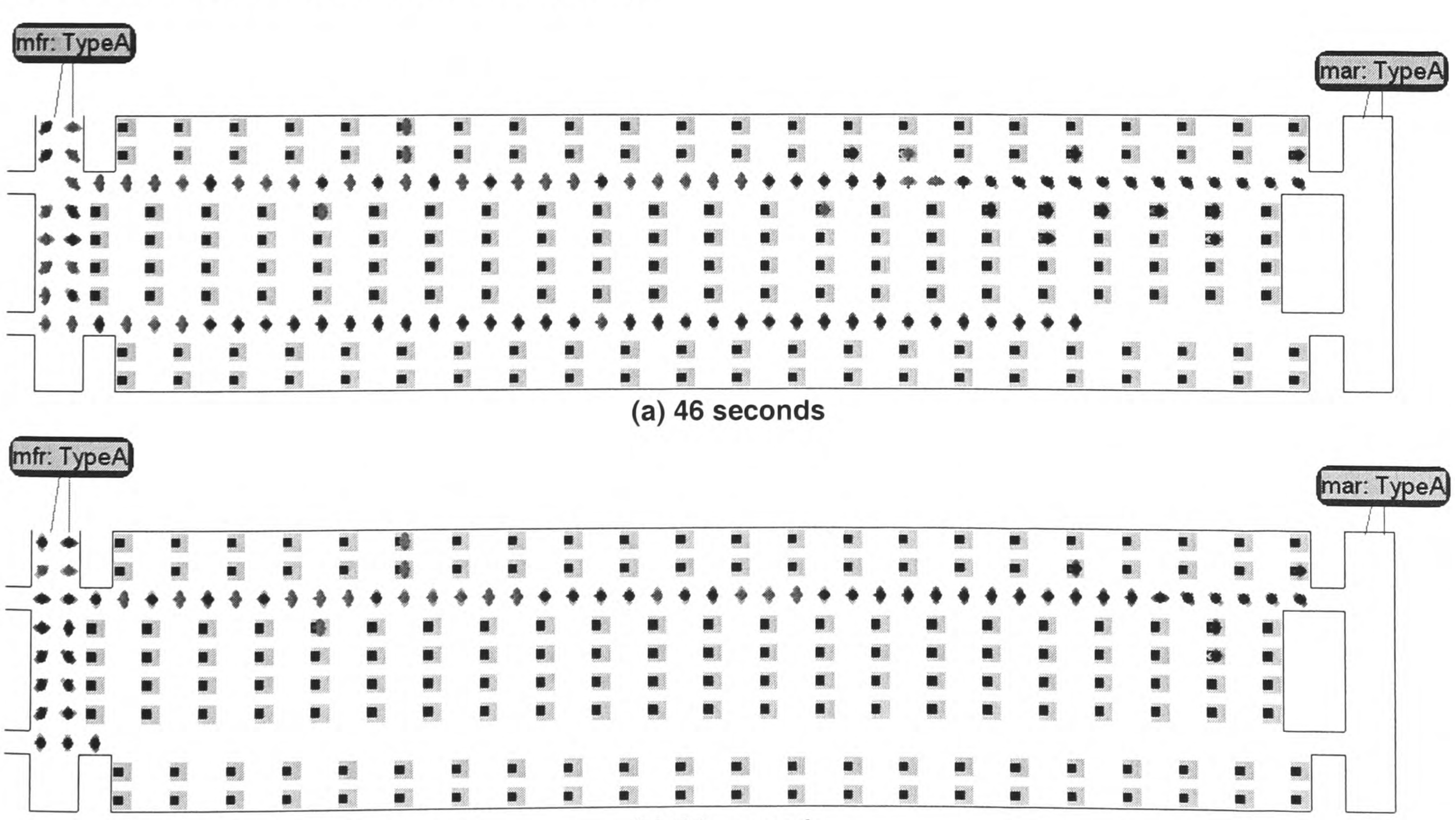
Various scenarios are modelled in order to demonstrate the performance of the model (see Table 58). The first set of scenarios (scenarios 1(a) and 1(b)) demonstrate aisle swapping in a 'typical' 90-second evacuation scenario. Following this some more specific scenarios are demonstrated that involve passengers aisle swapping to circumvent highly disabled passengers. A base-case scenario is first established (Scenario 2) that demonstrates the functionality of airEXODUS before these models were developed. This scenario is then repeated in scenario 3 having activated the aisle swapping models. Finally Scenario 2 and 3 are repeated under severe emergency evacuation conditions.

Table 58: Summary of demonstration scenarios

Scenario	Scenario Type	Summary of model configuration used
1(a)	90-seconds certification trial	a 90-second certification trial scenario in which the aisle swapping is deactivated
1(b)	90-seconds certification trial	a 90-second certification trial scenario in which the aisle swapping is activated
2	90-seconds certification trial	uses standard airEXODUS V3.0 features and consequently does not involve aisle swapping but contains an elderly slow moving passenger in the far aisle
3	90-seconds certification trial	a scenario in which the aisle swapping is activated and an elderly slow moving passenger is present in the near aisle,
4	Severe emergency conditions with smoke	Scenario 3(c) repeated in a fire scenario involving a cabin filled with uniform smoke

7.2.2.2 Scenario 1(a): A typical 90-second certification trial evacuation with the aisle swapping algorithms deactivated

This example simulates the evacuation of the hypothetical cabin section using a standard 90-second population and with the aisle swapping algorithms **deactivated**. This scenario is designed to establish a base-case against which the simulations using the aisle swapping algorithms can be compared. A key feature of this cabin is that the cross-aisle is wide enough to accommodate two passengers side-by-side. In most evacuations this lead to the far aisle evacuating its supply of passengers before the near aisle (see Figure 102). Consequently an empty aisle, albeit with a longer route, was available to some of the passengers towards the end of the evacuation. Despite this none of the near aisle passengers swapped to the far aisle and all of them waited patiently in the near aisle. The average TET from 100 simulations was 101.9 seconds and the average PET 55.3 seconds (see Table 59). On average passengers queued for 37.4 seconds and travelled 13.0 metres.



(a) 46 seconds

(b) 66 seconds

Figure 102: Graphic output from prototype airEXODUS in aisle swapping Scenario 1(a)

Table 59: Summary of the results of airEXODUS for aisle swapping scenario 1(a)

		TET (secs)	PET (secs)	CWT (secs)	Distance (metres)	Passengers that swapped aisles
Scenario 1(a)	Min	94.9	52.4	34.6	12.9	0
	Mean	101.9	55.3	37.4	13.0	0
	Max	110.0	58.9	40.9	13.1	0
	STDEV	2.8	1.3	1.2	0.0	0

7.2.2.3 Scenario 1(b): A typical 90-second certification trial evacuation with the aisle swapping algorithms activated

This example simulates the evacuation of the hypothetical cabin section using a standard 90-second population and with the aisle swapping algorithms activated. This simulation repeats the previous scenario but uses the aisle swapping algorithms. The model was run 100 times in order to gauge the frequency at which aisle swapping occurred and to assess its overall impact.

In some of these evacuations aisle swapping occurred. As an example one simulation is shown in Figure 103 and is typical of behaviour that was generated in other simulations in which aisle swapping occurred.

In this example for the first 60 seconds the evacuation progresses much as before and again the far aisle begins to exhaust its supply of passengers before the near aisle (see Figure 103(a)). However, in this example at 60 seconds a passenger in the near aisle becomes impatient and decides to swap to the empty far aisle. Others quickly followed him. Over the next 10 seconds many other passengers follow his actions and swap to the far aisle (see Figure 103(b) and (c)).

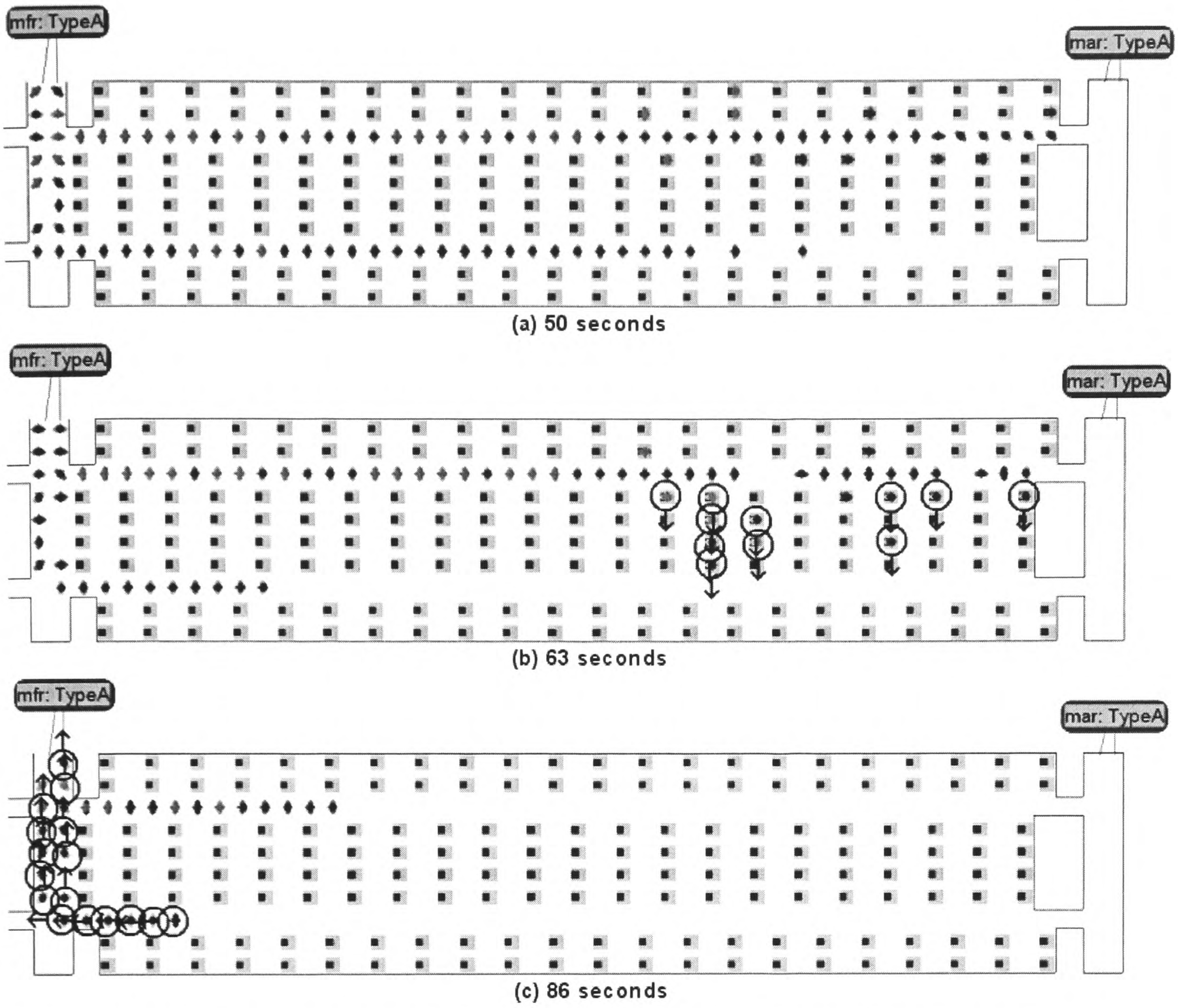


Figure 103: Graphic output from prototype airEXODUS in aisle swapping scenario 1(b) – Aisle swapping passengers are circled and arrowed

Whilst this example illustrates a typical instance in which passenger aisle swapping occurred it should not be viewed as being typical for the scenario as a whole. Indeed in 59% of evacuations no aisle swapping was recorded at all. However, when it did occur it involved on average 11 passengers and never fewer than four. In the evacuations in which aisle swapping took place the average CWT was marginally less that those in which aisle swapping did not occur (see Table 60). Likewise the average distance travelled by passengers was marginally increased.

In summary, the qualitative features of these evacuations and the frequency of aisle swapping behaviour compare favourably with observations from 90-second certification trials.

Table 60: Summary of the results of airEXODUS for aisle swapping scenario 1(b)

		TET (secs)	PET (secs)	CWT (secs)	Distance (metres)	Passengers that swapped aisles
Scenario 1(a)	Min	94.9	52.4	34.6	12.9	0
	Mean	101.9	55.3	37.4	13.0	0
	Max	110.0	58.9	40.9	13.1	0
	STDEV	2.8	1.3	1.2	0.0	0
Scenario 1(b) (ALL DATA)	Min	96.9	53.1	35.0	12.9	0
	Mean	101.8	55.5	37.3	13.1	4
	Max	109.2	59.0	40.8	13.7	24
	STDEV	2.6	1.2	1.2	0.2	6
Scenario 1(b) (41% that involved aisle swapping	Min	96.9	53.1	35.0	13.1	4
	Mean	101.1	55.3	37.0	13.3	11
	Max	108.1	57.6	39.3	13.7	24
	STDEV	0.0	0.0	0.0	0.1	0

7.2.2.4 Scenario 2: An evacuation with an elderly passenger but without aisle swapping

The following scenarios consider a more challenge scenario for the passengers in which an elderly and very slow moving passenger is placed within the cabin section. The elderly passenger is placed in the far aisle (see Figure 104) and has been assigned a slow walking pace of 0.14 metres/second. In order to provide a basis for later comparison aisle swapping has been **deactivated** in this scenario.

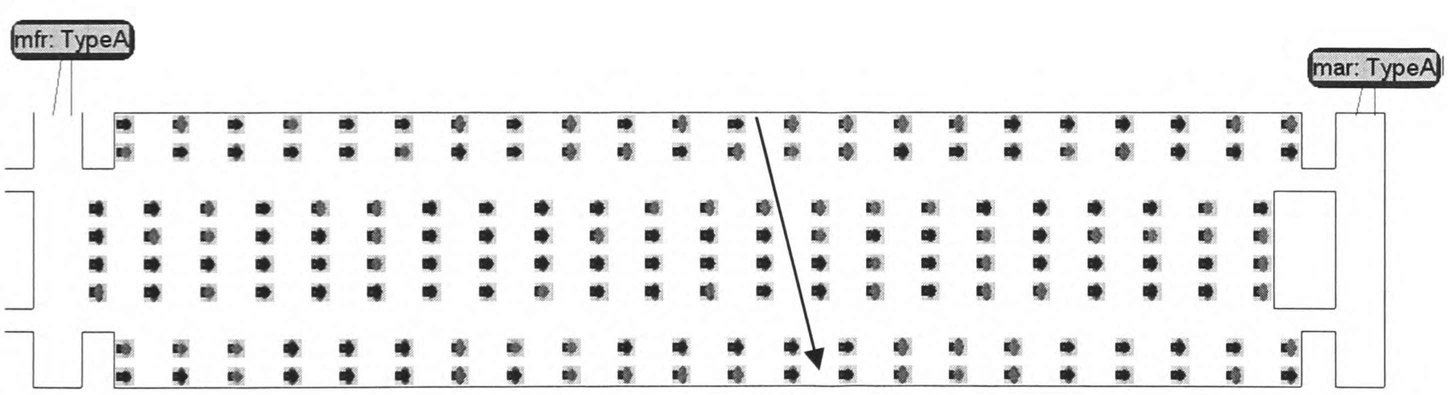
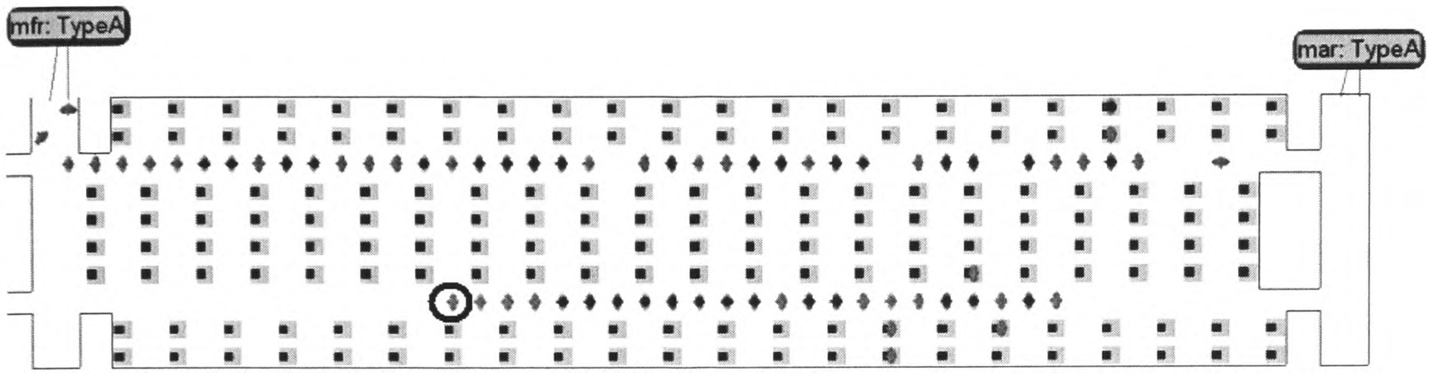


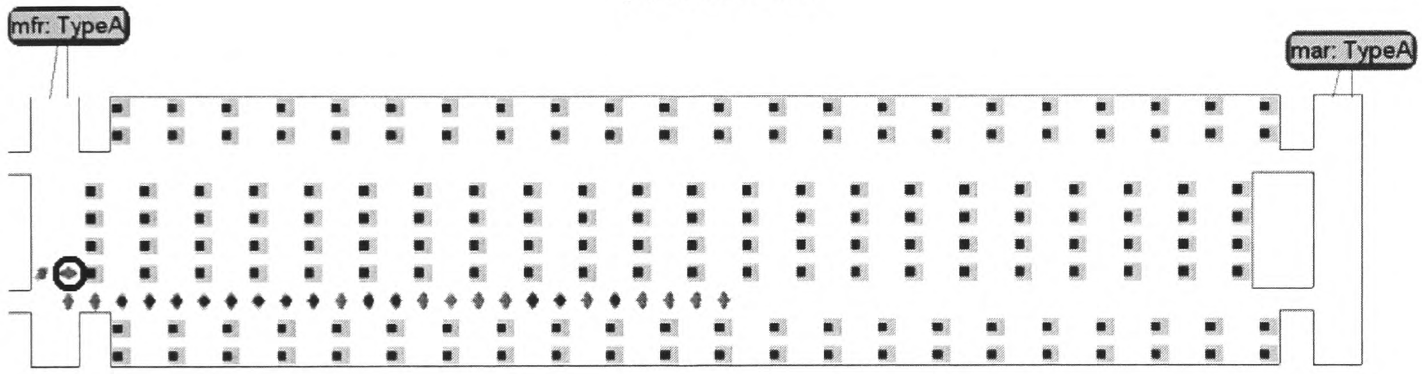
Figure 104: Example of the hypothetical cabin section

In the resulting evacuation passengers immediately make their way to the aisles and queue for the MFR exit. After 11.1 seconds the exit opens and passengers begin to evacuate. A near constant supply of passengers to the exits is provided by the near fully packed passenger aisles (see Figure 105 (a)). At 31 seconds the elderly passenger enters the aisle and is immediately unable to keep pace with the exit queue. Consequently a gap develops with those passengers behind experiencing significant sub-queue delays.

After 70 seconds the flow of passengers into the exit from the far passenger aisle has completely exhausted (see Figure 105(b)). Furthermore, the length of the near passenger aisle begins to decrease as most of its passengers have evacuated. At 93 seconds the near aisle has completed exhausted its supply of passengers (see Figure 105 (c)). At this stage there is no supply to the exit at all. This continues until the elderly passenger arrives at the cross-aisle after approximately 113 seconds (see Figure 105 (d)). Passengers who were behind the elderly passenger now begin overtaking in the cross-aisle area. The evacuation finishes at 140 seconds.



(a) 70 seconds



(b) 113 seconds

Figure 105: Graphic output from prototype airEXODUS in aisle swapping Scenario 2 – Elderly passenger is circled

Table 61: Summary of the results of airEXODUS for aisle swapping scenario 2

		TET (secs)	PET (secs)	CWT (secs)	Distance (metres)	Passengers that swapped aisles
Scenario 1(a)	Min	94.9	52.4	34.6	12.9	0
	Mean	101.9	55.3	37.4	13.0	0
	Max	110.0	58.9	40.9	13.1	0
	STDEV	2.8	1.3	1.2	0.0	0
Scenario 2	Min	136.0	57.2	38.5	12.9	0
	Mean	141.9	60.3	41.6	13.0	0
	Max	156.3	63.3	44.6	13.1	0
	STDEV	3.5	1.4	1.3	0.0	0

The behaviour generated from the model represents a very orderly evacuation in which the passengers' wait patiently at all times. When the evacuation was repeated the same pattern of behaviour was generated.

The average TET generated by 100 simulations was 141.9 seconds and the average PET was 60.3 seconds. Both averages have increased by large amounts when compared with the scenarios 1(a) and 1(b) without an elderly passenger. The next scenario investigates how the aisle swapping algorithm would allow passengers to circumvent the elderly passenger.

7.2.2.5 Scenario 3(a): an elderly passenger in the far aisle and aisle swapping activated

The next set of simulations demonstrates the application of the aisle-swapping prototype model to Scenario 2. The general trend of these evacuations is that during the early portion of the evacuation the qualitative features of the scenario are similar to the previous scenario. As before clear space at the back of the near aisle queue begins to develop from approximately 70 seconds onwards.

An example simulation has been presented in Figure 106. It can be seen in Figure 106 that the first passenger does not swap aisles until the 80th second. This feature results from the relatively low probability (0.042) of initiating aisle swapping derived from analysis of 90-second certification trials. In this example approximately 25-28 passengers are located behind the elderly passenger as such on average only 1-2 would be willing to initiate aisle swapping within the cabin section. In this example after 80 seconds aisle swapping is instigated (see Figure 106(a)). Once initiated others who are also experiencing delays decide to copy their behaviour and to swap aisles. As the evacuation progresses some more passengers experience delays and also decide to switch aisles (see Figure 106(b)).

This description represents but one instance of the model. In 32% of simulations no passengers decided to swap aisles. However, as witnessed in 90-second certification trials once a passenger initiates aisle swapping many others tend to follow. For example, in the simulations in which aisle swapping occurred a minimum of 11 passengers swapped aisles with the average number being 24 passengers (see Table 62).

Two additional sets of simulations were run. The first involved placing the elderly passenger in the near passenger aisle. In this batch 32/100 simulations contained aisle swapping with on average 11 passengers swapping aisles (see Figure 107(a)). In these simulations both the percentage of simulations in which aisle swapping occurred and the number of passengers involved was lower as a result of placing the elderly passenger in the near aisle. This results from the extra distance that passenger have to travel when swapping to an aisle that is further from the exit.

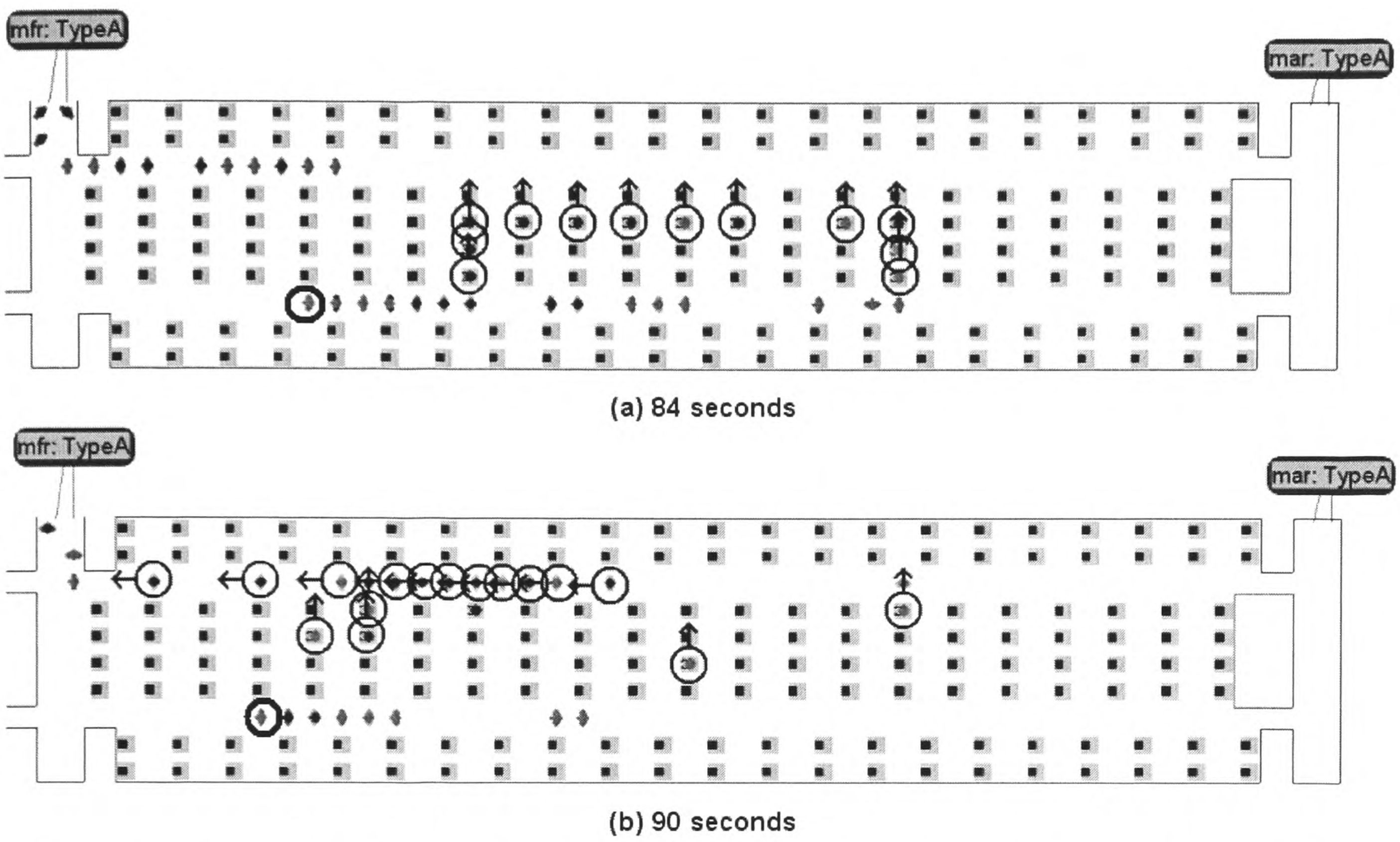


Figure 106: Graphic output from prototype airEXODUS in aisle swapping Scenario 3(a) – aisle swapping passengers are arrowed and circled – elderly passenger is circled

Table 62: Summary of the results of scenario 3

		TET (secs)	PET (secs)	CWT (secs)	Distance (metres)	Passengers that swapped aisles
Scenario 3 (ALL DATA)	Min	134.2	53.8	34.9	12.8	0
	Mean	141.7	57.7	38.8	12.9	16.3
	Max	158.4	63.9	45.0	13.1	29.0
	STDEV	4.8	2.3	2.3	0.1	11.7
Scenario 3 (68% aisle swapping simulations)	Min	134.2	53.8	34.9	12.8	11
	Mean	140.3	56.6	37.6	12.9	24
	Max	154.8	59.9	41.0	13.0	29
	STDEV	4.3	1.5	1.5	0.0	4

The second batch of simulations investigated the impact of placing an elderly passenger in both the near and far aisles. In this batch 75/100 simulations involved aisle swapping behaviour with on average 33 passengers swapping aisles (see Figure 107(b)). This represents an increase on the frequency of simulations and numbers involved when compared against Scenario 3. In these simulations the elderly passenger in the far aisle generally entered the aisle sooner than the near aisle elderly passenger. Thus, in most simulations some passengers from the far aisle that were ahead of the near aisle elderly passenger swapped to the near aisle. In addition as the elderly passenger in the far aisle reached the vestibule before the near aisle, some passengers in the near aisle swapped to the far aisle towards the end of the evacuation (see Figure 107((c)). The increased frequency of aisle swapping behaviour originates from the nature of the scenario and the number of passengers that are exposed to aisle swapping opportunities.

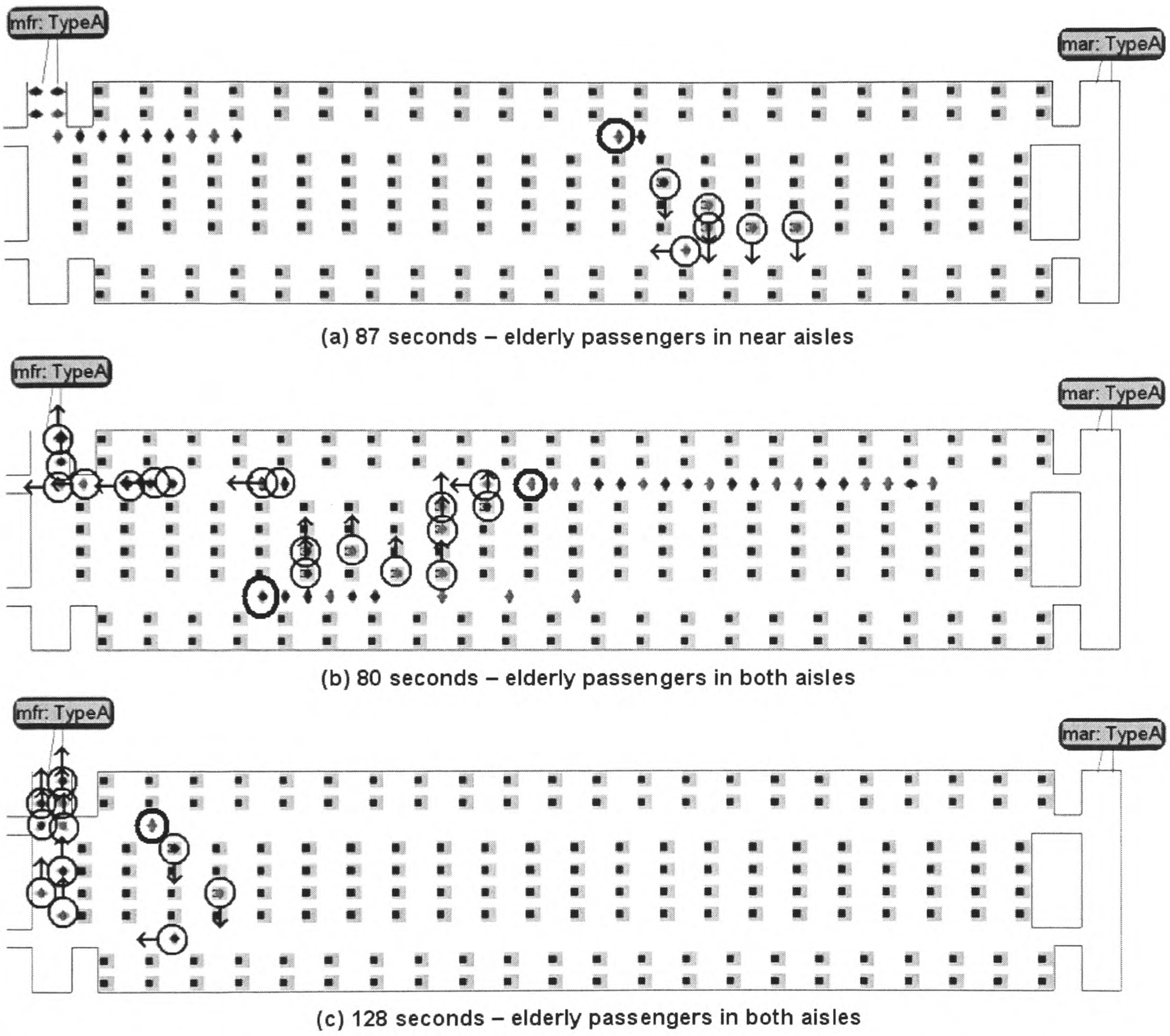
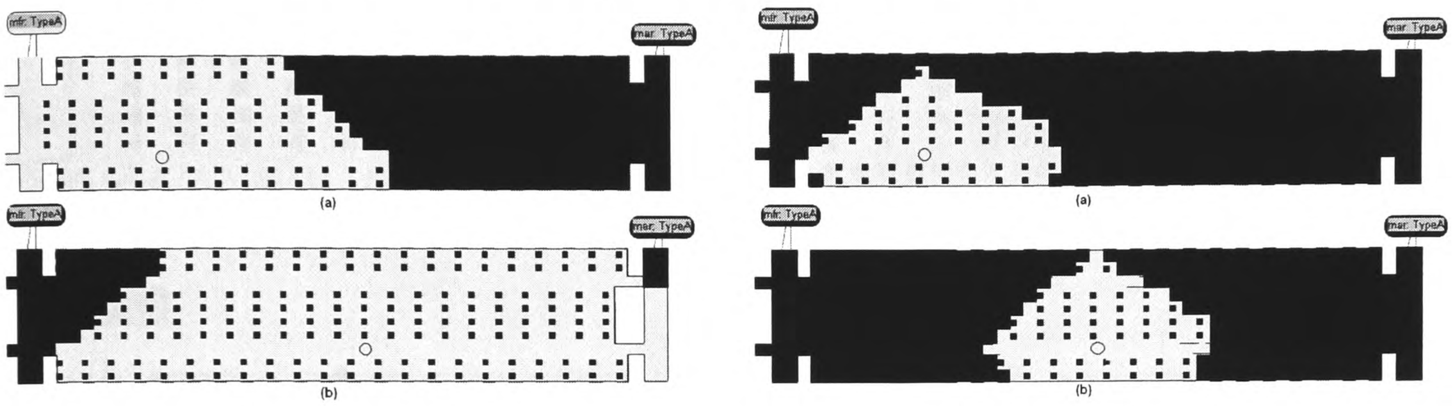


Figure 107: Graphic output from prototype airEXODUS with (a) an elderly passenger in the near aisle and (b) and (c) elderly passengers in both the near and far aisles – elderly passengers are circled – aisle swapping passengers are circled and arrowed

7.2.2.6 Scenario 4: Revisiting Scenario 3 in a fire scenario involving a cabin filled with uniform smoke

This scenario revisits scenario 3 in a smoke filled evacuation. As before a uniform smoke concentration with extinction coefficient of 0.5 is applied to the aircraft cabin. A description of one simulation that involved aisle swapping is now presented. The purpose of this example is to demonstrate the impact that reduced visibility in a smoke filled environment has upon the functionality of the aisle swapping algorithms. The cabin has been uniformly filled with smoke with an extinction coefficient of 0.5. During these simulations passengers were upright throughout their evacuation and did not elect to crawl underneath the smoke layer. Within the model the smoke conditions would have serve to slow the movement of passengers [40]. Using the smoke visibility calculations visibility of other passenger would be possible within a 4 metre range and exits would be visible within a range of 10 metres. Two examples of the visibility from these simulations are shown in Figure 108.



Visibility of signs   Visibility of passengers

Figure 108: Visibility of exits and other passengers from two different locations onboard the aircraft in Scenario 4(a) and 4(b) – passenger location is ringed

The resulting evacuation initially progresses much the same as Scenario 3. However, unlike the example shown in the discussion of Scenario 3, a passenger from the near aisle swaps to the far aisle area ahead of the elderly passenger. After this event the near aisle area ahead of the elderly passenger empties and some of the passengers behind the elderly passenger in the far aisle swap to the near aisle (see Figure 109(a)). However, this evacuation significantly differs from scenario 3 at 63 seconds as some of the passengers from the near aisle swap to the back of the far aisle (see Figure 109(b)). This behaviour is different to Scenario 3 and results from their inability to see the elderly passenger in the far aisle. As the length of the far aisle queue diminishes others follow (see Figure 109(b)). These passengers soon catch the slow moving far aisle queue and then noticing the relatively free space in the far aisle swap back to the near aisle (see Figure 109(c)). Eventually, all of the near aisle passengers have swapped to the far aisle.

The results of 100 simulations indicate that in every simulation aisle swapping occurred. Indeed the average number of passengers that aisle swapped increased from 25 in Scenario 3(a) to 57 passengers. The high number of passengers that aisle swapped results in part from setting the probability of considering aisle swapping to one. In addition restricted vision caused some of the passengers at the back of the near aisle to swap to the back of the far aisle earlier than before. This resulted from their inability to see any slow moving passengers in the far aisle.

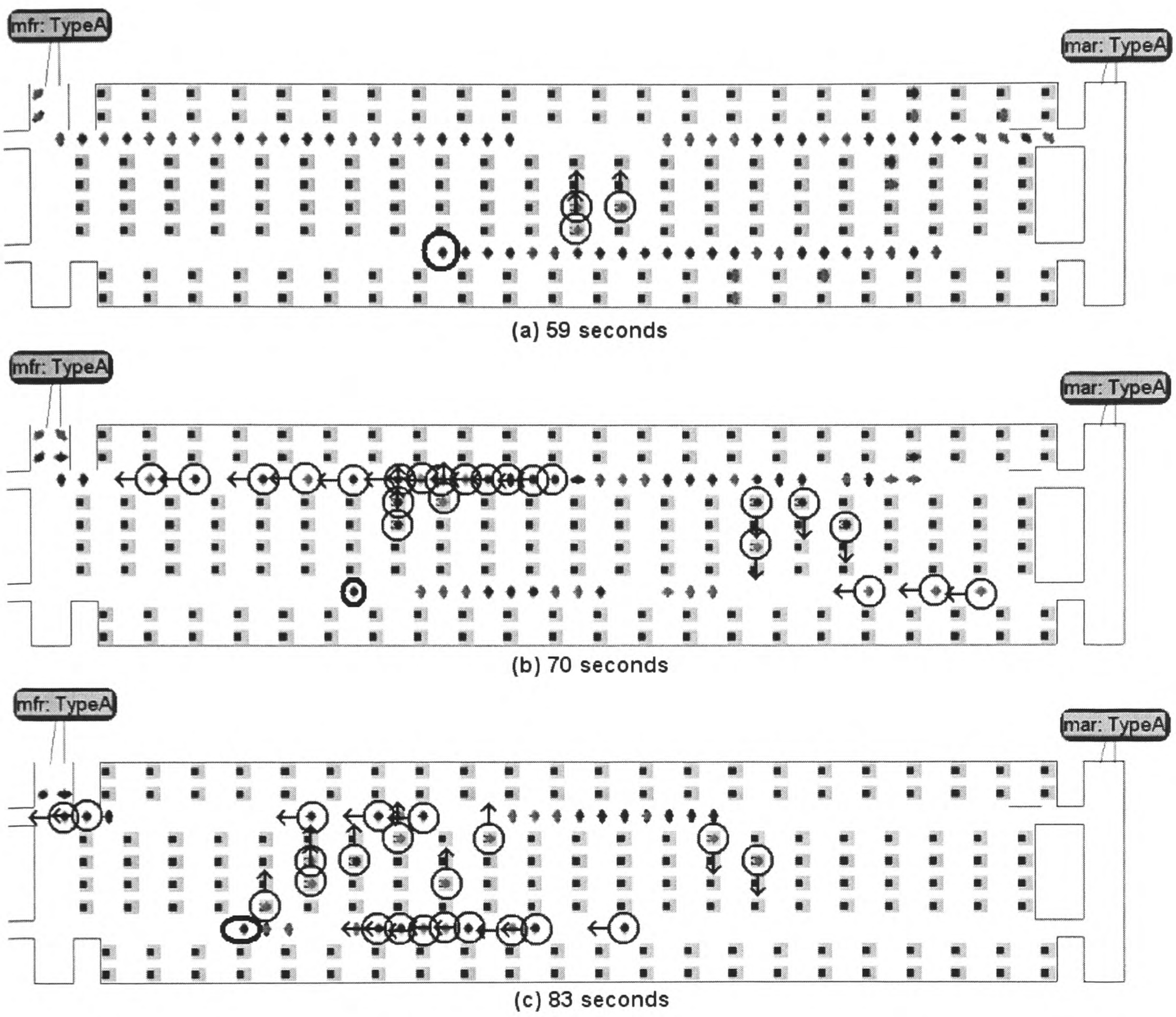


Figure 109: Prototype airEXODUS graphic output for aisle swapping scenario 4 – elderly passenger is circled – aisle swapping passengers are circled and arrowed

Table 63: Summary of the results of scenario 3 and scenario 4

		TET (secs)	PET (secs)	CWT (secs)	Distance (metres)	Passengers that swapped aisles
Scenario 3 (ALL DATA)	Min	150.5	67.4	48.1	13.1	0
	Mean	160.6	61.0	41.9	13.0	25
	Max	160.4	73.9	54.6	13.1	59
	STDEV	157.1	64.0	44.9	13.0	18
Scenario 4 (100% with aisle swapping)	Min	140.1	56.4	36.2	13.0	32
	Mean	153.9	61.4	41.1	13.4	57
	Max	164.0	71.9	51.6	13.9	74
	STDEV	5.1	3.1	3.0	0.2	11

7.2.3 Summary of results

In a certification type scenario 41% of simulations displayed aisle-swapping behaviour (see Table 64). This number compares favorably with that witnessed in 90-second certification trials (in certification trials aisle swapping occurred in 59% of the cabin zones of wide-bodied aircraft). In these scenarios the main impact that the aisle swapping algorithms had were qualitative with more realistic movement patterns being generated within the cabin. The inclusion of this behaviour did not significantly affect average TET, PET or CWT generated from 100 runs of the model. This result suggests a lack of sensitivity in the 90-second certification methodology to different patterns of behaviour inside the cabin.

Scenarios 2-4 involved an elderly passenger being placed in the cabin section. In these scenarios the aisle swapping algorithms had a significant affect on the average PETs, CWTs and distance traveled by passengers (the TET remained the same as in all simulation the last passenger to evacuate was the elderly passenger). In these, more complex scenarios, the qualitative behaviour had a greater impact on the results than was found in the 90-second certification scenarios.

Table 64: Summary of average results from airEXODUS

	Average TET (secs)	Average PET (secs)	Average CWT (secs)	Average Distance (metres)	Average Passengers that swapped aisles	Average % simulations with aisle swapping
Scenario 1(a)	101.9	55.3	37.4	13	0	0%
Scenario 1(b)	101.8	55.5	37.3	13.1	4	41%
Scenario 2	141.9	60.3	41.6	13	0	0%
Scenario 3	141.7	57.7	38.8	12.9	16.3	68%
Scenario 4	160.6	61	41.9	13	25	100%

7.3 A model to represent seat jumping as a method of optimising an evacuation route in severe emergency evacuation scenarios

A more extreme form of route optimisation behaviour involves passengers shortening their evacuation route through climbing over seating. This type of behaviour was investigated in detail and the results presented in Chapter 5. This section uses the knowledge gained in Chapter 5 to construct a computer based model to represent this behaviour.

7.3.1 The prototype model

A finding of the investigation in Chapter 5 was that seat climbing was rarely cited in passenger accounts from accidents that do not involve fire. Likewise seat climbing was practically non-existent from video recordings of 90-second certification trials. Seat climbing was however cited, albeit at low frequency (29 citations from 222 accounts), in accidents that involve cabin burn-through. Given this, seat climbing behaviour will only be considered as an option during severe emergency evacuations that involve fires. In 90-second certification trials and real accidents that do not involve fire seat climbing will not be considered by passengers. The following models should therefore be considered in the context of severe evacuations from life threatening situations.

The investigation in Chapter 5 found numerous types of seat climbing that involved passengers,

(a) climbing over a seat adjacent to the exit from another seat row,

(b) climbing over one or more previously collapsed or un-collapsed seats from a position in a seat row some distance from the exit,

(c) climbing over one or more previously collapsed or un-collapsed seats from a position in an aisle some distance away from the exit.

(d) climbing over a seat adjacent to the exit from a position in the aisle,

Models are developed to cover all of these forms of seat climbing behaviour and are presented in this section. Before describing the details of each model some of the shared features of all of the sub-models are described.

The analysis of the evacuation data (see Chapter 5), suggested that a passenger's decision to jump seating is based on their perception of their current situation. Chapter 5 also suggested that the location of a passenger within the cabin influenced the likelihood of a passenger seat climbing. In addition, seat climbing actions appeared to trigger other seat climbing actions in nearby passengers. This analysis suggests that factors such as their location in the cabin, the levels of congestion they are experiencing, the presence of smoke and/or toxic gas, the proximity of other seat climbing passengers and the path that they took over seating may all influence a passenger's decision process.

These behaviours have been implemented into the airEXODUS evacuation model. A summary of the key components of the decision-making process used in the seat jumping algotrithm is shown in Figure 110. The aspects of the passenger decision-making process when seat climbing detailed in the following sections are:

a) determining when a passengers patience has been exceeded,

b) whether they are willing to consider climbing seating,

c) choosing a route of seating, and

d) terminating seat climbing behaviour.

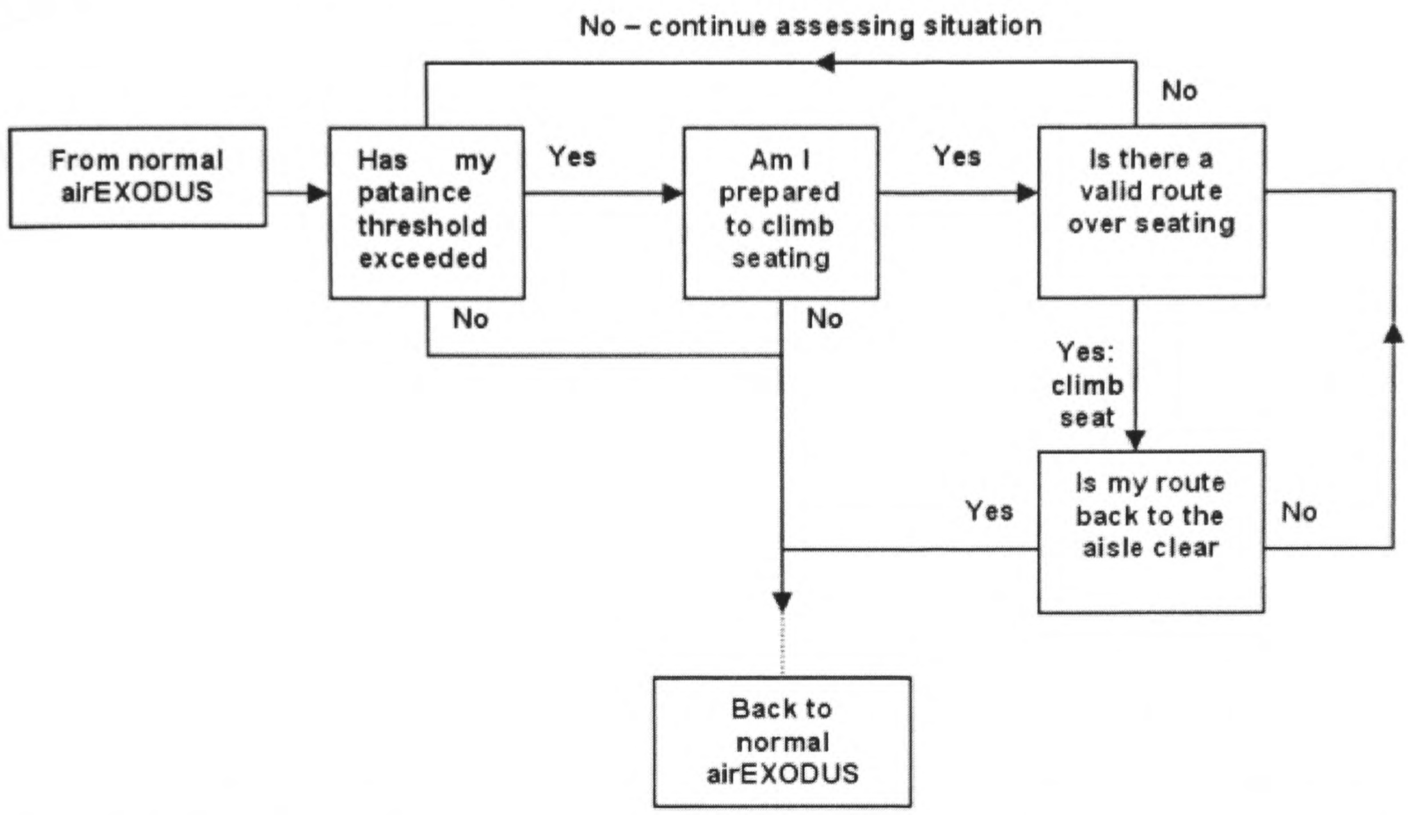


Figure 110: Flow diagram for passengers seat climbing from any area other than a row immediately adjacent to a Type-III exit

7.3.1.1 Getting impatient and finding a route over seating

Within this model it was decided that once passengers become impatient with their current route they would begin to assess whether or not there is an alternative route over seating. The patience attribute is used to make this determination within the model.

In reality the level of patience would be related to how greatly passengers' value their current location. For example, a passenger at the back of a queue would most likely become impatient to the point of considering a route over seating sooner than one at the front. With respect to seat climbing the location of the passengers is categorised as being either,

(a) adjacent to a Type-III exit row and in seating,

(b) some distance from an exit and in seating,

(c) some distance from an exit and in an aisle,

(d) adjacent to the Type-III exit row but in the aisle.

Passengers that are located in aisles are likely to feel more content with their current position than those a similar distance from the exit but located in seating. Likewise a passenger that is located in a seat row that is adjacent to a Type-III exit is likely to feel more content with his position than one who in a seat row that is 5 rows from the exit. Given this, it is proposed that the length of time required for passengers to lose their patience to a level where they would consider seat climbing be affected by their location.

Within the prototype their location is determined via the four categories shown previously (a,b,c or d). Each category is ordered according to how it may be perceived by a passenger relative to other categories. Each category is then assigned a modifier that affects their passengers' patience threshold when considering seat climbing (see Table 65).

Table 65: Precieved worth of passengers' locations and the proposed patience modifier used in the model

Category	Comparative rating of position	Patience modifier
A	Third best	100%
B	Worst	50%
C	Second worst	150%
D	Best	200%

Using this scheme, a passenger with a patience of 3 second would start looking for alternative routes after a delay of 6 second (3*200%) if they were at the front of the queue. However the same passenger would start looking for alternative routes after only 4.5 second (3*150%) if they were located at the back of a queue and within seating. Recall that these models only apply to fire scenarios in which behaviour is likely to be quite extreme.

One they have exceeded their patience threshold seat climbing behaviour is considered. The next stage of the model concerns passengers selecting an appropriate alternative route over seating. This method of route selection applies to all seat climbing behaviour developed in this chapter, be it seat climbing from aisles, from within seating or from rows adjacent to Type-III exits.

Within this model passengers examine all of the visible seats within their row or if they are positioned in an aisle adjacent seat rows. This is performed using a variation of the best-first graph search that was described previously (see Section 7.2.1.1). This assessment is based on vision and as such is limited according the current visibility determined using the smoke visibility algorithms (see Figure 111) outlined earlier (see Section 6.1.2.2).

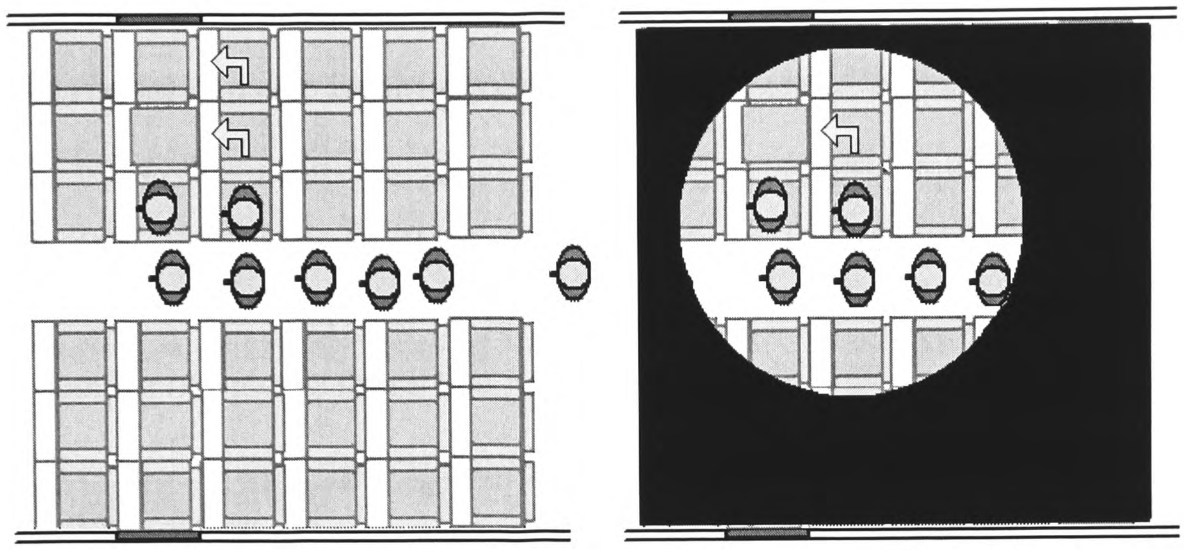


Figure 111: An example of passenger's seat climbing options (a) without and with (b) smoke

Whilst forming a list of viable routes the obstacle values of the seat nodes and connecting arcs are contrasted against the agility of the passenger. This determines whether the passenger is physically capable of climbing the seat and consequently whether a route is valid or invalid. The obstacle value of a particular route is affected by the status of the chair, i.e. upright or collapsed. Thus, a passenger who determines that they do not have the agility to climb over an erect seat may attempt to climb a collapsed seat. Within airEXODUS the mobility attribute is affected by both the smoke concentration of the atmosphere (see Table 66) and their exposure to narcotic gases (see Table 67). Where both factors interact the lower (i.e. the more severe) of the two values is assumed [50]. The mobility reductions reflect the decrement in travel speed derived by Jin [146-148] during various experiments in which volunteers moved through smoke filled environments. An assumption of the airEXODUS model is that a similar reduction in the performance capability would occur to passengers' level of agility. Thus within airEXODUS the smoke and narcotic irritant gases affect the mobility attribute (where a value of 1 represents full mobility and 0 total immobility) which in turn is used to scale passengers' agility and travel speed. This implication of this is that

Table 66: The Relationship between agility and smoke concentration [146-148]

Smoke Concentration (1/m)	Affect on mobillity (%)
0.0 - 0.1	None
0.2	-8%
0.3	-24%
0.4	-43%
0.5	-64%
>0.5	Crawl rate

Table 67: The Relationship between agility and smoke concentration [50]

FIN	Affect on mobility (%)
0.00 - 0.89	0
0.90 - 0.95	-10%
0.96 - 1.00	-20%

in smoke filled environments, the ability of passengers to climb seats will be reduced. In dense smoke conditions, passengers would be unable to climb seats.

Within this model a route is only considered if is empty, i.e. unoccupied by another passenger. In addition, previously collapsed seating represents a more attractive route than a seat than one that is fully erect. Therefore, within the model when passengers are examining a route over seating they will prefer if possible not to climb over un-collapsed seating but to use those that have already been collapsed by other passengers.

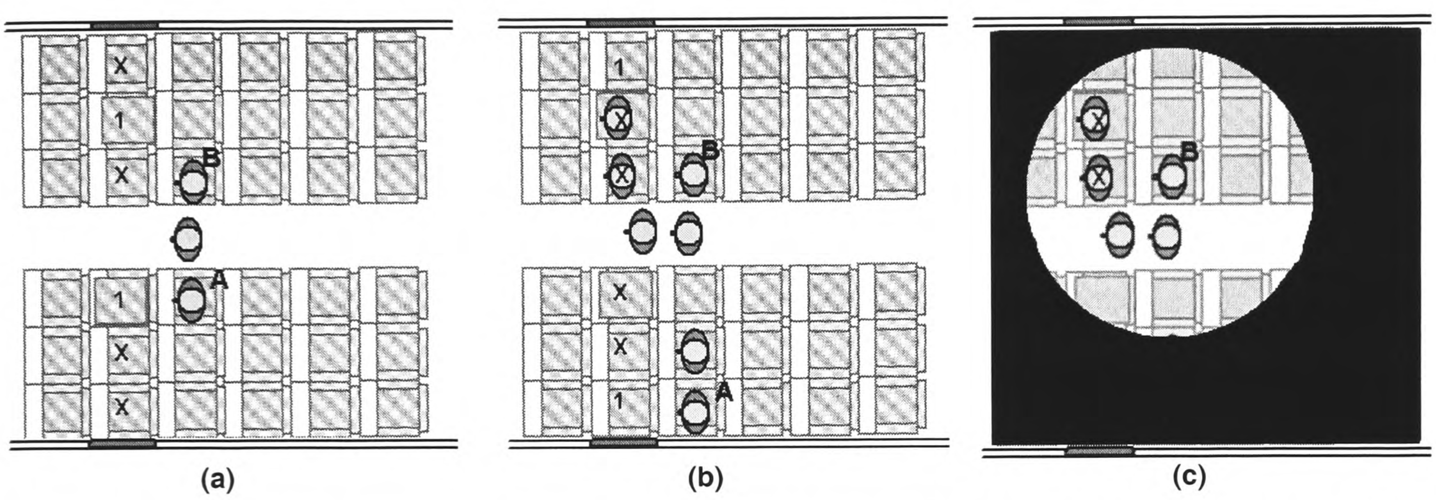


Figure 112: Three examples of passenger seat climbing route preferences (1 denoates the preferred route, X's denote considered but rejected routes)

The logic of the route selection aspect of the model is best explained through the use of examples. In Figure 112(a) both passenger A and B are considering seat climbing. In this example passenger A would prefer the seat immediately in front of him (denoted with a 1 in Figure 112(a)). Passenger B would prefer the seat slightly to the right (denoted with a 1 in Figure 112(a)). These were both chosen as they were the nearest collapsed seat. Figure 112(b) demonstrates another scenario. In this example passenger A and B are again considering seat climbing behaviour. In this example passenger A only has one option as alternative routes are blocked by passengers. Passenger A would therefore be forced to consider climbing over the un-collapsed seat immediately in front of him (denoted by a 1 in Figure 112(b)). Passenger B would also be forced to climb over an un-collapsed but unoccupied seat (denoted by a 1 in Figure 112(b)) as more local options are occupied by other passengers. Figure 112(c) demonstrates shows the options of passenger B in dense smoke conditions using the same set-up as (b). In this example passenger B would conclude that no seat climbing options are available as he would be unable to see the vacant seat adjacent to the exit.

This concludes the description of the common features of the seat climbing sub-models. What now follows are specific rules that are applied according to the four categories of seat climbing behaviour outlined previously.

7.3.1.2 (a) climbing over a seat adjacent to the exit from another seat row

A first observation from the analysis of AASK was that many passengers who were seated in the row that is adjacent to a Type-III exit row were prepared to climb over the single row of seating that stood between them and the exit. This section details a model for passenger seat climbing behaviour when adjacent to Type-III exits. Before continuing with this discussion, it should be mentioned that on modern aircraft (post Manchester in 1985) seating adjacent to Type-III exits cannot be collapsed. That is not to say that passengers will not climb over the seating, but just that the seats will not collapse when they do so and that climbing them will be more difficult.

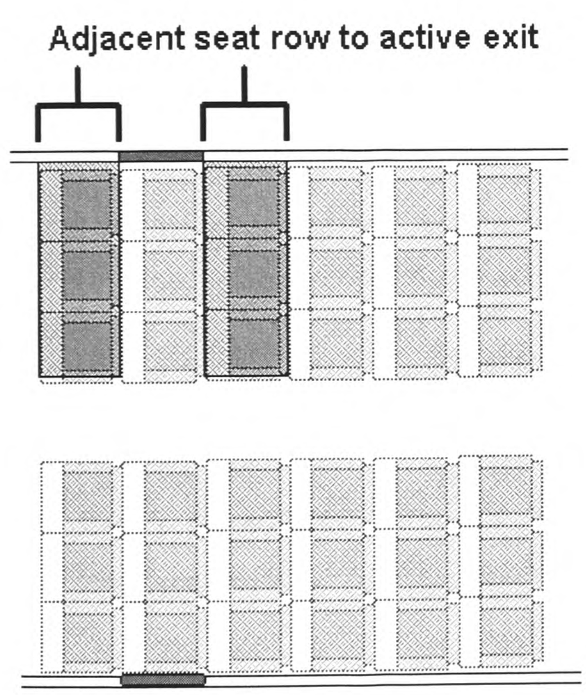


Figure 113: Example of seat rows adjacent to a Type-III exit

airEXODUS has the capability of simulating the collapsing of seats as passengers climb over them. However, an additional feature has been provided within the prototype model that allows the users to stipulate that seat rows adjacent to Type-III exits cannot be collapsed (see Figure 113). In this way it is possible to model past accidents in which exit seat rows were collapsible and modern evacuations in which seats adjacent to the Type-III exit cannot be collapsed.

It is proposed that all of the passengers that are seated adjacent to the over wing exit row (see Figure 113) and have exceeded their relevant patience threshold should consider climbing over seating to reach the exit row. This does not mean that all of the passengers would climb over the seating. Some passengers would not have any alternative routes available, as a consequence of them not having the agility or all visible routes being blocked by other passengers. Alternatively, their route via the aisle may be free; consequently they would not consider this behaviour at all as they would not have exceeded their appropriate patience threshold.

It is recommended that only when a passenger has exceeded their relevant patience threshold (150%*patience), has a viable route over seating, has the agility and his/her normal route via the aisle is blocked by other passengers will seat climbing be undertaken by passengers in rows adjacent to active Type-III exits.

7.3.1.3 (b) some distance from an exit and in seating

This section of the seat climbing model deals with seat climbing that occurs in seating that is not adjacent to Type-III exit rows. This differs from the previous model as the investigation of human behaviour in Chapter 5 indicates that passengers may not always choose to climb seating when able too. In addition passengers that are located some distance from the exit would have the option of climbing more than one seat row.

Firstly, seat climbing is only considered by passengers that have their 'normal' route through the aircraft blocked by other passengers and have been waiting a time in excess of their Patience attribute. In this situation passengers are located in essentially the worst location possible. As such their patience threshold will be very low.

According to the analysis of AASK, seat climbing in locations distant from exits is less likely than seat climbing when adjacent to the exit row. As such it is not recommended that every passenger consider seat-climbing behaviour. Using the data from AASK (see Chapter 5) we can determine the likelihood of a passenger seat climbing account being reported in a fire scenario. This will form the basis for determining whether a passenger is likely to climb over seating within this model.

It was suggested in Chapter 5 that the likelihood of passengers seat climbing was affected by age. Any probability distribution that is developed should be at least a function of age. Likewise a finding of previous research was that the average age of female seat climbers was lower than that of males. As such the data should also be split according to gender. The construction of a probability distribution that is both a function of age and gender is detailed below.

Figure 114(a) shows the frequency of seat climbing accounts from burn-through scenarios as a function of age for both male and females in AASK. It can be seen that the majority of accounts are from young passengers. Also apparent from Figure 114(a) is that the female frequency distribution is shifted to the left, i.e. towards lower ages. This supports the finding of previous research [103]. Closer examination reveals that the male curve comprises 13 and the female curve 14 accounts of seat climbing. Figure 114(b) shows the frequency distribution of passenger ages for both males and females from ALL burn-through scenarios contained within AASK V3.0. The male curve comprises 128 and the female curve 94 survivors.

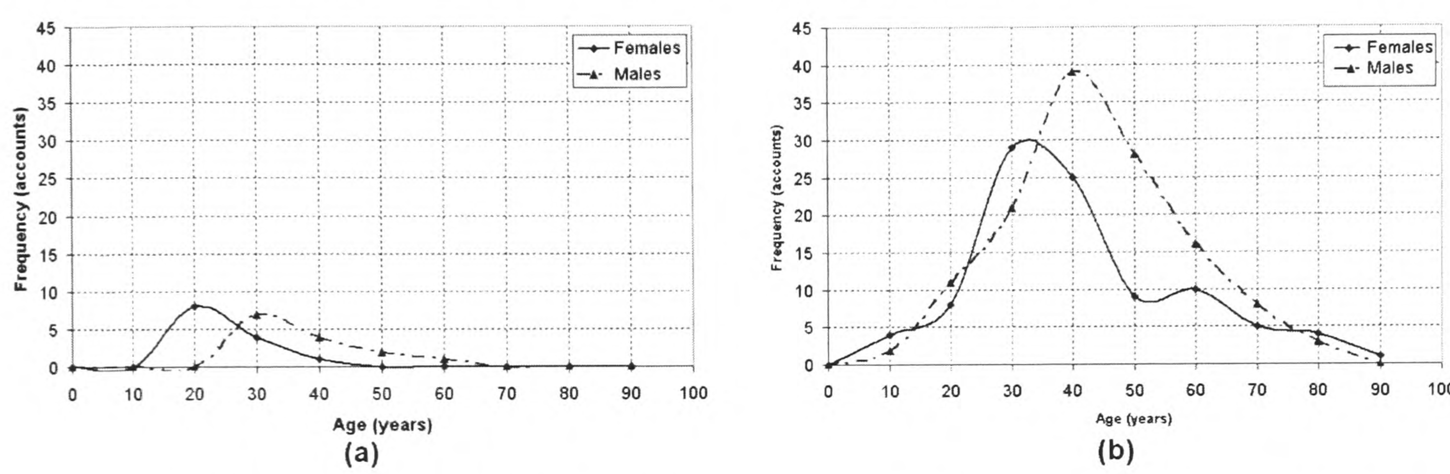


Figure 114: (a) the frequency of seat climbing descriptions as a function of age from burn-through scenarios and (b) the frequency distribution of survivors from burn-through accounts as a function of age

Overlaying the number of accounts of seat climbing and survivors from burn-through scenarios shows the relative frequency of accounts as a function of age (see Figure 115). Using these two distributions a probability of seat climbing can be calculated via dividing the total survivors by the number of seat climbing accounts at each age group.

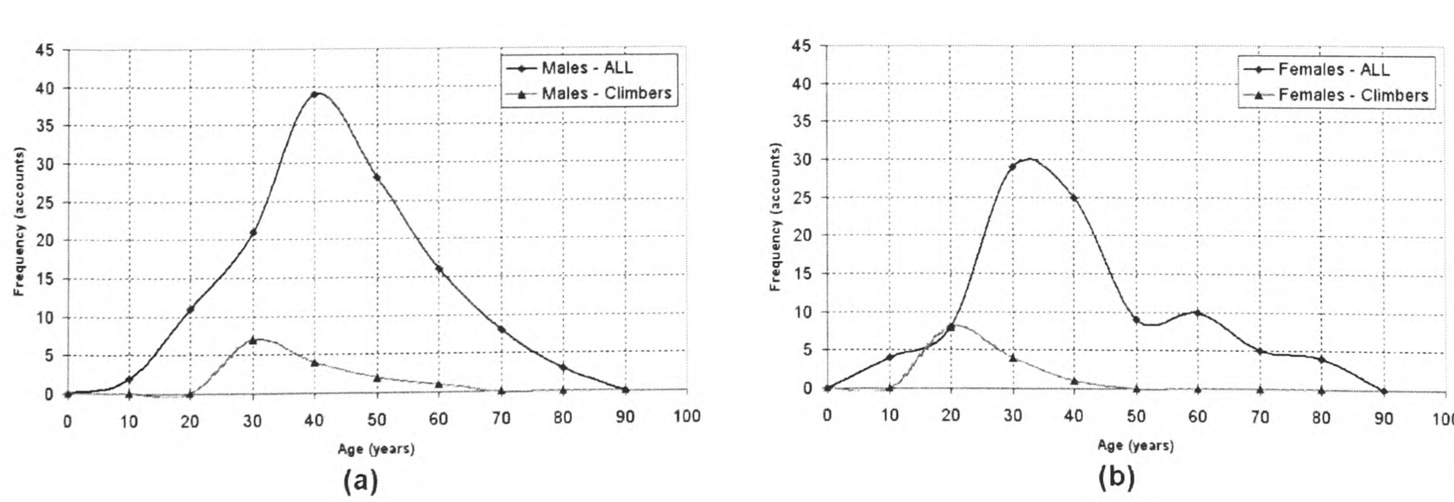


Figure 115: Frequency of seat climbing accounts plotted against the total number of survivors from burnthrough scenarios for (a) males and (b) females

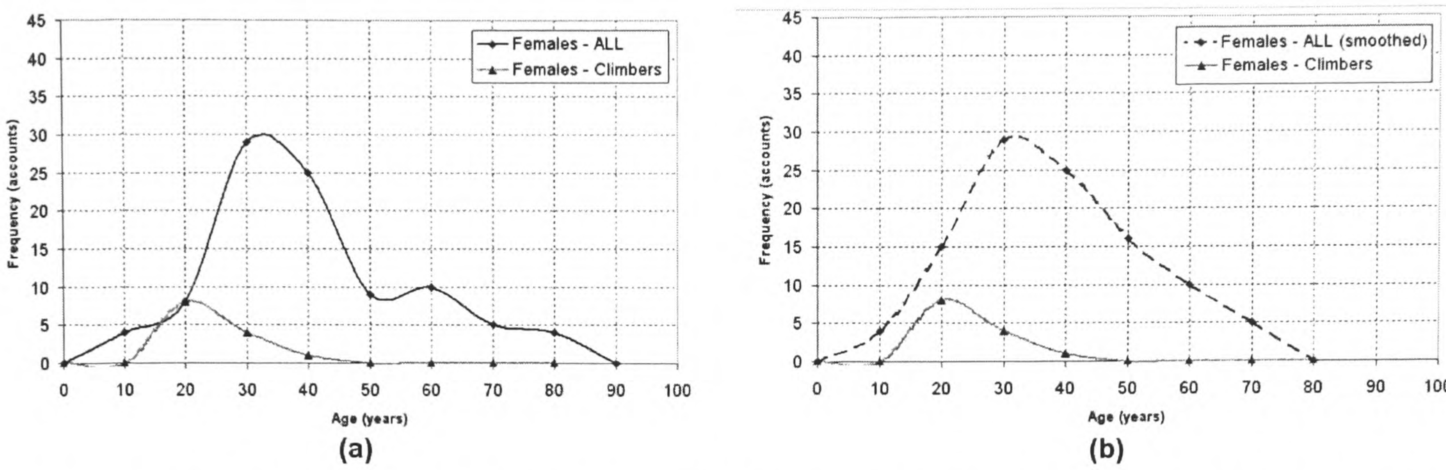


Figure 116: The (a) actual freqeuncy of seat climbing accounts plotted against the total number of survivors from burnthrough scenarios for females and (b) a smoothed version of the actual curve

From examination of Figure 115(a) it is apparent that the female probability distribution contains a very high value for 10-20 year old females (nearly a probability of 1). This is indicated by the two curves practically converging for ages between 10 and 20 years (see Figure 115(a)). This implies that almost every female passenger between the ages of 10 and 20 years will climb over seating. This does not appear sensible and is considered to be an anomaly in the data resulting from the limited size of the dataset (In total 94 female datapoints). To alleviate this problem and to produce a more normal distribution the female curve, a 'smoothed' frequency distribution curve has been generated (see Figure 116(b)) which was used in place of the total number of female passenger accounts in determining the probability of a seat climbing account being in AASK (see Figure 117). The 'smoothed' curve has had the number of accounts from passengers between ages 10-20 and 40-50 increased slightly. This had the effect of generating a more normal distribution that is broadly similar in structure to its male equivalent (see Figure 114(b)). Using the data shown in Figure 117 a series of uniform distributions have been calculated (see Table 68) that can be used within the model to determine the likelihood of a passenger deciding to climb seating according to their gender and age.

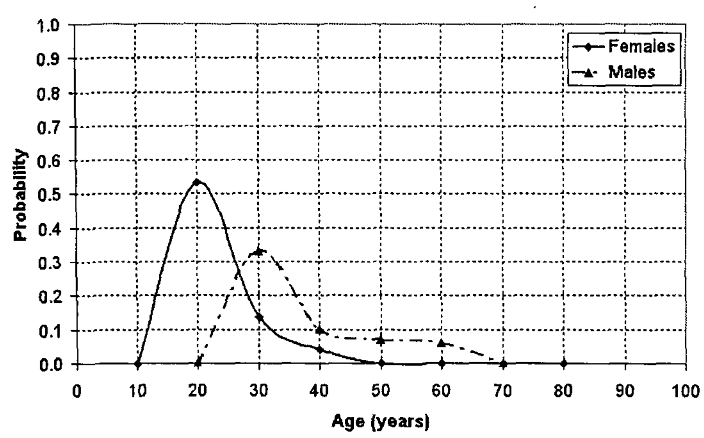


Figure 117: The probability distribution of climbing seating in burnthrough scenarios

Table 68: Uniform probability distributions extracted from Figure 117

Age group	Probability for males	Probability for females
<10	0	0
10-20	0	0.533
20-30	0.333	0.138
30-40	0.103	0.040
40-50	0.071	0
50-60	0.063	0
60>	0	0

Within the model passengers are assigned a probability value based on the above functions that are used throughout their evacuation in the appropriate regions of the aircraft.

A finding of the AASK analysis was that seat climbing accounts were clustered together with many passengers who were sat adjacent to each other describing similar actions. To reflect this, a further feature of this model is that when a passenger climbs a seat he/she increases the likelihood of others in the vicinity choosing a similar course of action. Based on the investigation of AASK the 'vicinity' was set to 1 metre within the model. This was chosen as similar accounts were recorded from passengers in adjacent seats and adjacent seat rows. However, there was insufficient data on which to reliably base an increase in the likelihood of seat jumping. Thus an arbitrary increase to the seat jumping probability of 10% was used when a local instance of seat climbing, i.e. within a 1 metre range) is witnessed. Whilst this value is arbitrary, a percentage increase is justified by the findings of the AASK investigation.

Using the above probabilities a determination can be made for each passenger as to whether they are prepared to climb seating.

The stage of the model concerns passengers that have exceeded their patience threshold and are presumed to be willing to climb seats. This stage involves the passenger searching for viable routes using the method described earlier. Should a valid route be found then the passenger climbs the row of seating, if not they continue waiting and assessing local conditions for appropriate routes.

Having climbed a row of seating, it may be viable for them to climb another. Recall that this section of the model applies to passengers located some distance from the exit. A method for determining whether a passenger will continue climbing seats or stop and attempt to enter an aisle is then required. Within the model this is achieved through having the passenger evaluate his/her route to the nearest aisle. Within the model passengers do not cease seat jumping behaviour if their route to the aisle is blocked by other passengers. A further feature of this assessment is that a small area - 2 nodes within the model running backwards - of the aisle discharge must be completely empty of passengers. Should these conditions not be met then passenger would continue climbing over seating until either they arrive at a bulkhead/exit or there is space to move back into the aisle.

7.3.1.4 (c) some distance from an exit and in an aisle

From the analysis of the AASK database it was apparent that in some instances passengers were willing to leave an aisle in order to climb over seating. This section details a model that would allow passengers to take this action.

The fundamentals of this model are essentially the same as that described previously, however deciding to climb seating from a position in an aisle is considered a more extreme form of seat climbing as the passenger is leaving the ergonomically unrestricted space of an aisle in favour of the constricted environment of seating rows. To reflect this it is recommended that passengers only consider this option once they have been waiting a relatively long time. This has already been incorporated into the model via the application of the patience modifiers (see Table 65). With respect to passengers' willingness to climb over seating the probability values that were shown in the previous section are also employed in these circumstances also.

The main difference between this model and that of the previous section is that passengers located within an aisle have more movement options. The routines used when searching for alternative routes is therefore more complex as the passenger may have options both left and right (see Figure 118).

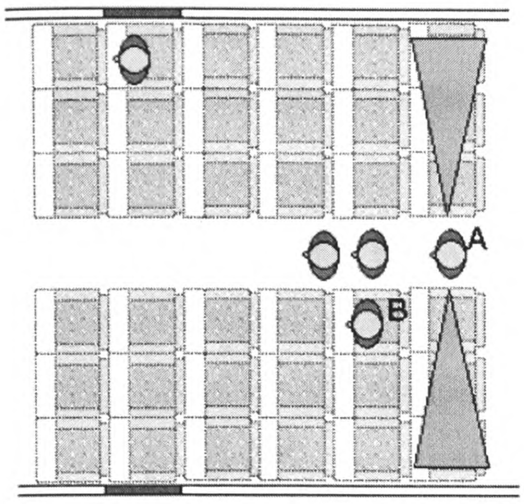


Figure 118: Potential routes from an aisle

Within this prototype model passengers should follow the preferences as defined earlier and choose the route of least resistance, i.e. the nearest collapsed seat or failing that the nearest un-collapsed seat. The route selection is again limited according to the smoke visibility algorithms. Where two options exists that are equally close the passenger the nearest viable seat to the passenger's current exit choice is used.

Having found a route the passenger would initiate the seat climbing behaviour using the rules of the previous section. Having climbed over a seat row the algorithm reverts to that of seat climbing from seats that are not adjacent to the exit row as defined in the previous section.

7.3.1.5 (d) adjacent to the Type-III exit row but in the aisle

The final seat climbing scenario considered in these models is a passenger located in the aisle and located in line with the seat rows that are adjacent to the Type-III exits. As mentioned previously, this represents the best position when compared with those previously considered. As such passenger patience is doubled at these locations (patience*200%).

Should however, a passenger become impatient and have his route blocked for some time then he/she may consider climbing seating. The probabilities formulated previously are used to make this determination. Should the passenger be impatient and willing to climb seating then he/she searches for an alternative route over seating. This is performed using the methods outlined previously however the following additional rules are included.

If both Type-III exits are available then the passenger will search both left and right (see Figure 119(a)), however should only one of the Type-III exit be active then he/she will search the seating on the active side only (see Figure 119(b)). This excludes behaviour whereby a passenger decides to climb seating on the opposite side of the aircraft to the active exit (see Figure 119(c)).

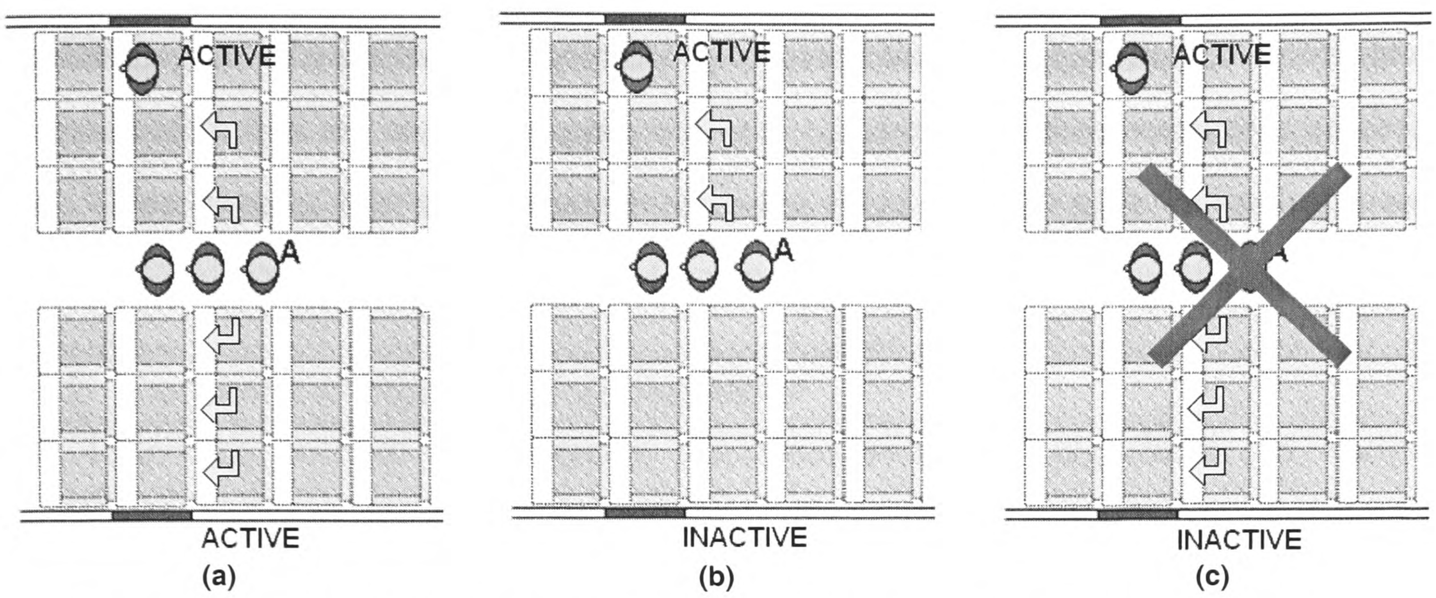


Figure 119: Route selection for passenger A when adjacent to a Type-III exit and in an aisle

7.3.1.6 Combining seat climbing and passenger aisle swapping

In real emergency evacuations passengers may be presented with the option of swapping aisles or seat climbing. The patience thresholds that are used when a passenger has his route blocked differ according to the type behaviour, seat climbing or aisle swapping. In all circumstances a higher patience threshold must be exceeded to consider seat climbing than to consider aisle swapping. Consequently, the patience thresholds form a hierarchy and dictate that a passenger in an aisle would consider aisle swapping before seat climbing.

Should a passenger that is experiencing a delay in an aisle not find a suitable aisle to swap to, i.e. it may be moving more slowly than his current aisle or the route to the aisle may be blocked, then he would continue to wait until their seat climbing patience threshold is exceeded. At this point the seat climbing models would activate and they would consider new and more extreme options. This may allow the circumventing of delays via seat climbing.

Another feature of this model is that when a passenger is aisle swapping and his route becomes blocked by another passenger, seat climbing may be considered using the appropriate rules of the seat climbing model. Thus, a passenger could begin to swap aisles but resort to seat climbing. Close consideration of the current rules for seat climbing reveal that in this situation a passenger could decide to return back to the aisle that he recently departed. This could lead to the bizarre behaviour in which a passenger seeks to circumvent a slow moving passenger, however seat climbs to avoid a blockage whilst aisle swapping and then returns to the same aisle only to do the same again. To remedy this anomaly the aisle swapping algorithm is interrogated by passengers that are aisle swapping and seat climbing and have recently climbed a seat. This ensures that the passenger uses the most optimal aisle following a seat climb.

7.3.2 Examples of seat climbing behaviour

The following section demonstrates the aisle swapping algorithms in various scenarios (see Table 69) to give an indication how it would operate. These scenarios are designed to demonstrate the functionality of the algorithms rather than demonstrating their use in realistic applications (real applications of the algorithms are the subject of the next chapter). As such they are somewhat simplistic.

Table 69: Summary of demonstration scenarios

Scenario	Scenario Type	Summary of model configuration used
1(a)	Severe emergency	A narrow bodied evacuation in severe emergency conditions without fire or smoke
1(b)	Severe emergency	A narrow bodied evacuation in severe emergency conditions with a uniform smoke atmosphere
1(c)	Severe emergency	A narrow bodied evacuation in severe emergency conditions with a smoke hazard that increases to a specified level
2(a)	Severe emergency	Aisle Swapping Scenario 4(a) (an elderly passenger in the far aisle) in severe emergency conditions without fire and smoke
2(b)	Severe emergency	Aisle Swapping Scenario 4(a) (an elderly passenger in the far aisle) in severe emergency conditions with a smoke hazard that increases to a s specified level

Scenario 1 demonstrates the seat climbing algorithms performance in a narrow-bodied aircraft evacuation (see Table 69). First a base-case is established (Scenario 1(a)) in which evacuation is accomplished without using the models developed in this work. This is followed by two scenarios that each investigates the sensitivity of the algorithms to the type of smoke hazards.

Scenario 2 demonstrates two cases in which the seat climbing algorithms is used in a wide-bodied aircraft evacuation. In these scenarios **aisle swapping** and **seat climbing** can both occur. For simplicity the aisle swapping demonstration scenarios that was described in the previous set of aisle swapping demonstrations as Scenario 4 will be used (see Section 7.2.2.6). Recall that in this scenario an elderly passenger is located in the far aisle is used . The results of aisle swapping demonstration scenario 4 will serve as the base-case results against which two different scenarios involving seat climbing and aisle swapping are assessed. The first scenario that is simulated (Scenario 2(a)) demonstrates the functionality of the models in clear air whilst the second (Scenario 2(b)) demonstrates the evacuation with a smoke hazard.

In all of these scenarios the populations were generated using the standard 90-second population available within airEXODUS and each set of scenarios was repeated 100 times.

7.3.2.1 Scenarios that involve seat climbing

Scenario 1(a): A narrow bodied evacuation in severe emergency conditions but without fire and smoke

This scenario uses the model configuration from validation case 5 (see Section 4.5.1). However, in this scenario the seat climbing algorithms are **activated**. In addition passenger exit choice and redirection has been disabled. Indeed the only additional behaviour in this scenario when compared with validation case 5 is the deployment of the seat climbing algorithms. This scenario is somewhat artificial as it demonstrates the use of the seat climbing algorithms in completely clear air. When used properly the seat climbing algorithms would be activated automatically by airEXODUS when the modelled passengers ascertain severe evacuation conditions, i.e. when they detect significant levels of smoke, radiation or heat (see Section 6.1.2.3). As such seat climbing would not be likely in clear air conditions. This scenario is however interesting as it indicates the performance of the seat climbing alrogithms performing under optimal – clear air – conditions. Finally, this scenario was run 100 times within the model.

The first observation from the simulations was that a different pattern of seat climbing resulted from each run of the simulation (see Figure 120 and the pattern of collapsed seats). This results from the adaptive mechanisms that underpin the model and the stochastic element imposed through age/gender based probabilities of climbing seats. Whilst passenger agility remained the same in each simulation, the probability assigned to each passenger varied from simulation to simulation, thus a passenger that climbed a seat in one simulation may have decided not to in another.

The behaviour generated by the model is apparent from examining the path that the passengers took en route to the exits. This can be seen in Figure 121. It can be see that on occasions passengers decided to leave aisles to travel over seating (see Figure 121(a)) and that some passengers decided to climb the entire route to the exit (see Figure 121(b)). The propensity for passengers to use ready broken seating as opposed to climbing un-collapsed seats is also apparent from the paths that passengers travelled (see Figure 121 (b),(c),(d) and (f)). Finally an instance of a passenger breaking down a single row adjacent to the Type-III exit is also evident (see Figure 121(f)).

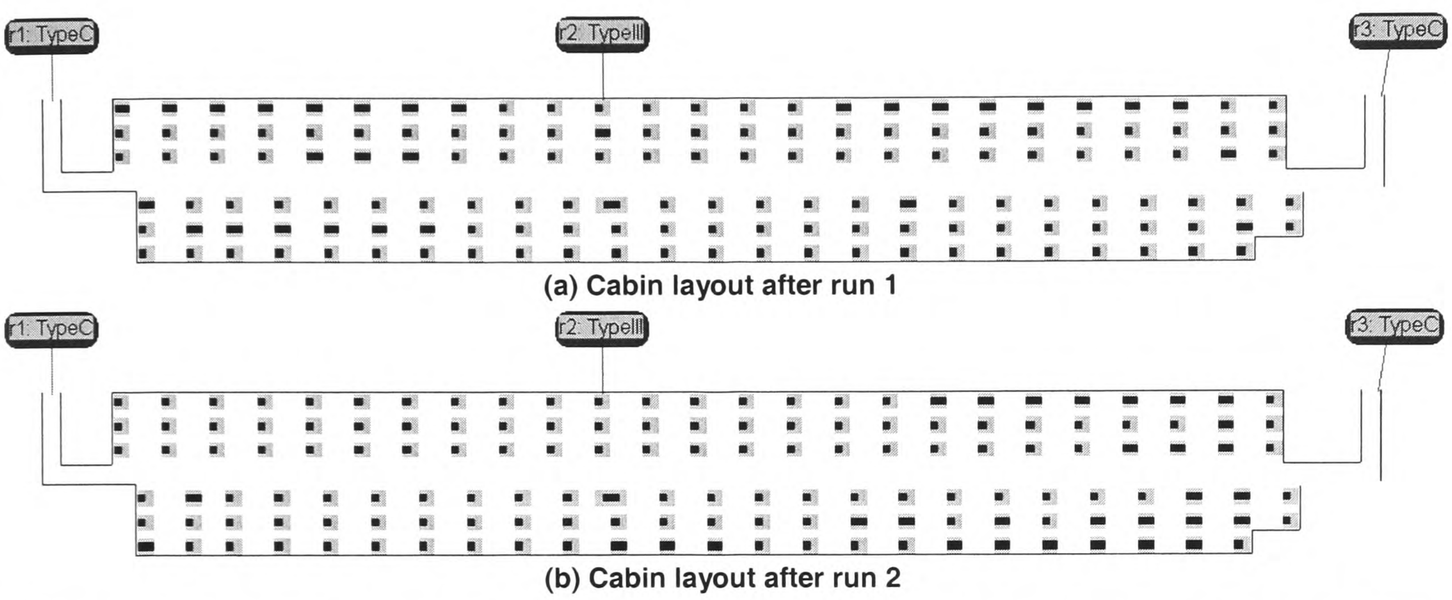


Figure 120: Two runs of scenario 1(a) showing the stochastic variation in the scenario (collapsed seats have a solid black bar running horizontally through them)

The results from 100 simulations are presented in Table 70. It can be seen that on average 12 passengers per simulation climbed over seating. This shows some correlation to the number of accounts found in burn-through scenarios (number of accounts in Los Angles, Manchester and Dallas Fort-Worth were 8, 16 and 3 – this excludes questionable data (see Section 5.4)). Within the model the average number of seats travelled was four rows. Within burn-through scenarios in AASK there were 31 accounts of seat climbing, of these 16 did not specify the number of rows that they climbed and the average from those that did was 1.73 seat rows. This amount of seat climbing generated by the model does not correlate so well with the data contained within AASK.

The lack of quantitative correlation maybe related to the lack of a fire hazard in this scenario and therefore higher mobility and agility than would typically be expected in a seat jumping scenario. In an accident with a fire, the thermo-toxic affects of the fire would serve to reduce agility and mobility and thus reduce the number of passengers that are physically able to seat climb. In addition visibility would be impaired in a smoke atmosphere. The next two scenarios explore this through the simulation of two different smoke hazards.

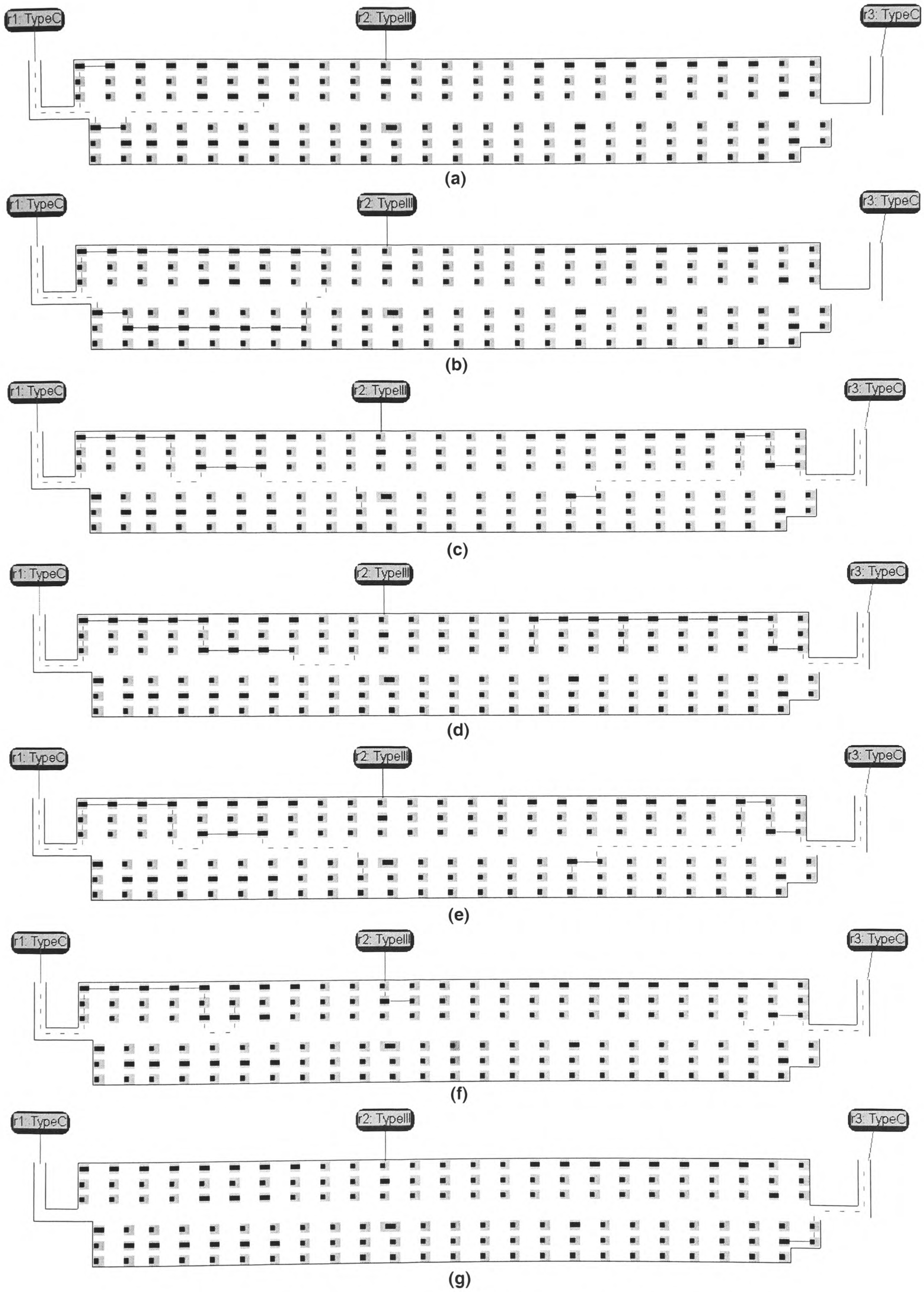


Figure 121: Paths treavelled by passengers that seat climbed in Figure 120(a)

Table 70: Summary of seat climbing scenario 1(a)

		TET (seconds)	PET (seconds)	CWT (seconds)T	Distance (seconds)	Aisle Swapped (pax)	Seat Climbed (pax)	Average No. Rows (Rows)
1(a)	Min	65.9	35.0	21.5	6.6	0	5	2
	Mean	74.7	37.0	23.4	6.7	0	12	4
	Max	87.5	39.6	25.9	6.9	0	20	6
	STDEV	4.7	0.9	0.9	0.1	0	3	1

1(b) narrow bodied evacuation in severe emergency conditions without fire but with a uniform smoke atmosphere

This scenario simulates exactly the same configuration as 1(a) with the exception of a uniform smoke hazard with an extinction coefficient of 0.5. Using the smoke visibility algorithms developed in Chapter 6 it can be calculated that the visibility of other passenger is reduced to 4 metres (2/0.5) in this scenario. Since the cabin is small and passengers only consider local aspects when seat climbing this level of visibility is not expected to impact upon the vision of passengers when considering seat climbing behaviour. This scenario is akin to an internal fire scenario in which the fire has developed for some time within the cabin prior to the start of the evacuation.

In this scenario it can be seen that none of the passengers were able to climb seating. Within the model a smoke concentration of 0.5 has the affect of reducing mobility to such a low level that climbing un-collapsed seating is physically impossible for all passengers (see Table 66). Since the smoke concentration is always set an extinction coefficient of 0.5 and all of the seats begin in an upright position, seat climbing never occurs in these simulations.

In a real evacuation the smoke concentrations would to some degree vary from location to location and would increase and decrease throughout the developing fire scenario. To explore this in more detail a developing smoke hazard is modelled in the next scenario.

Table 71: Summary of seat climbing scenario 1(b)

		TET (seconds)	PET (seconds)	CWT (seconds)	Distance (seconds)	Aisle Swapped (pax)	Seat Climbed (pax)	Average No. Rows (Rows)
1(a)	Min	65.9	35.0	21.5	6.6	0	5	2
	Mean	74.7	37.0	23.4	6.7	0	12	4
	Max	87.5	39.6	25.9	6.9	0	20	6
	STDEV	4.7	0.9	0.9	0.1	0	3	1
1(b)	Min	65.6	34.7	21.6	6.5	0	0	0
	Mean	75.0	37.0	23.8	6.5	0	0	0
	Max	90.2	38.9	25.6	6.6	0	0	0
	STDEV	5.1	0.9	0.8	0.0	0	0	0

1(c) narrow bodied evacuation in severe emergency conditions with a smoke hazard that increases to a specified level

This scenario models a developing smoke hazard. The hazard begins with an extinction coefficient of 0 and increases at a rate of 0.025 per second to a maximum extinction coefficient of 0.5. As with the previous scenario visibility is not an important factor during this evacuation. The maximum extinction coefficient is achieved 20 seconds into the evacuation.

This scenario represents either an external or internal developing fire scenario. The purpose of this scenario is to demonstrate the degree of seat climbing that can occur within the model during a developing smoke hazard scenario. The aim is not to obliterate passenger vision completey, hence the smoke values do not exceed 0.5.

In these simulations on average 10 passengers decided to climb an average of 3 seat rows. Contrasting this against the results of Scenario 1(a) – this scenario without smoke - reveals average decreases to both the number of seat climbers and the number of rows that were climbed.

Table 72: Summary of seat climbing scenario 1(c)

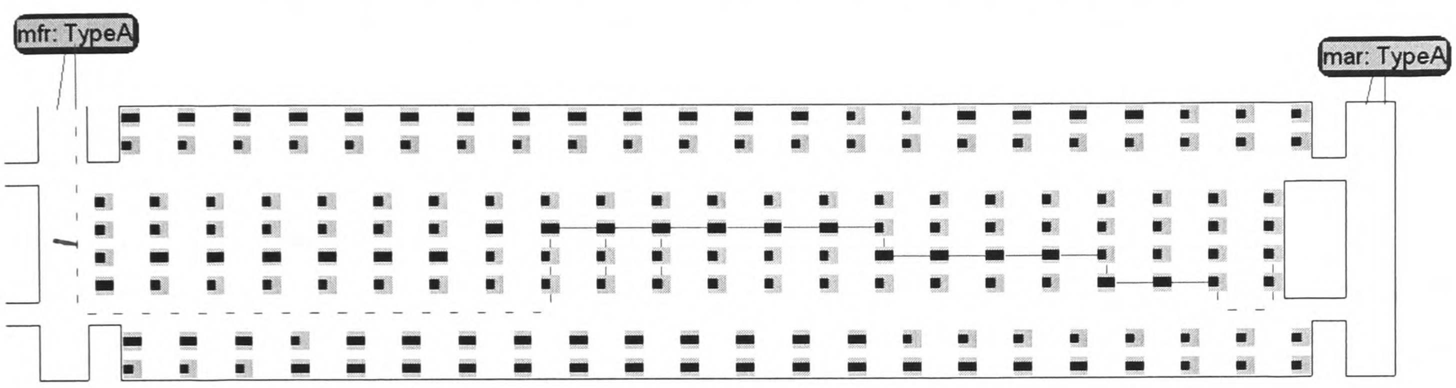
		TET (seconds)	PET (seconds)	CWT (seconds)T	Distance (seconds)	Aisle Swapped (pax)	Seat Climbed (pax)	Average No. Rows (Rows)
1(a)	Min	65.9	35.0	21.5	6.6	0	5	2
	Mean	74.7	37.0	23.4	6.7	0	12	4
	Max	87.5	39.6	25.9	6.9	0	20	6
	STDEV	4.7	0.9	0.9	0.1	0	3	1
1(b)	Min	65.6	34.7	21.6	6.5	0	0	0
	Mean	75.0	37.0	23.8	6.5	0	0	0
	Max	90.2	38.9	25.6	6.6	0	0	0
	STDEV	5.1	0.9	0.8	0.0	0	0	0
1(c)	Min	64.9	35.0	21.5	6.6	0	3	2
	Mean	75.2	37.1	23.6	6.7	0	10	3
	Max	98.0	40.2	26.6	6.8	0	17	5
	STDEV	5.5	0.9	0.9	0.1	0	3	1

Most of the seat climbing occurred during the first 20 seconds of the evacuation. However some occurred after 20 seconds and involved passengers climbing collapsed seats. The reduction in the number of rows that passengers travel over seating results from the smoke hazard affecting passenger mobility. In these simulations as the smoke hazard develops passengers' mobility decreases until climbing over un-collapsed seats becomes impossible. Thus some passengers that were seat climbing or may have considered seat climbing in future find themselves unable to and are forced to follow a less difficult route. Some passengers with high agility are always able to climb over collapsed seating during the evacuation.

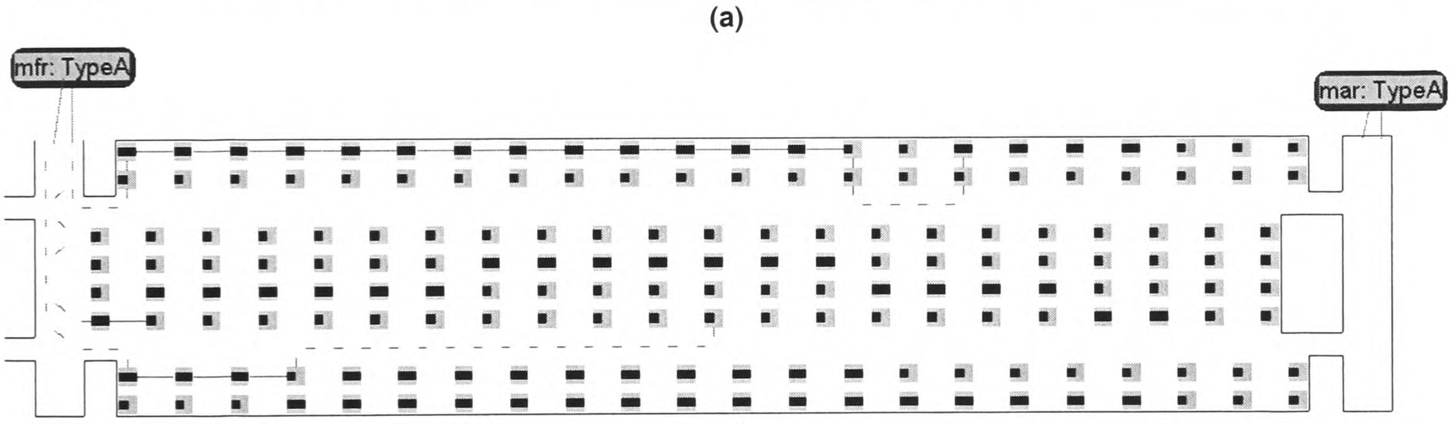
7.3.2.2 Scenarios that involve aisle swapping and seat climbing

2(a) Revisiting Aisle Swapping Scenario 4(a) (an elderly passenger in the far aisle) in severe emergency conditions without fire and smoke

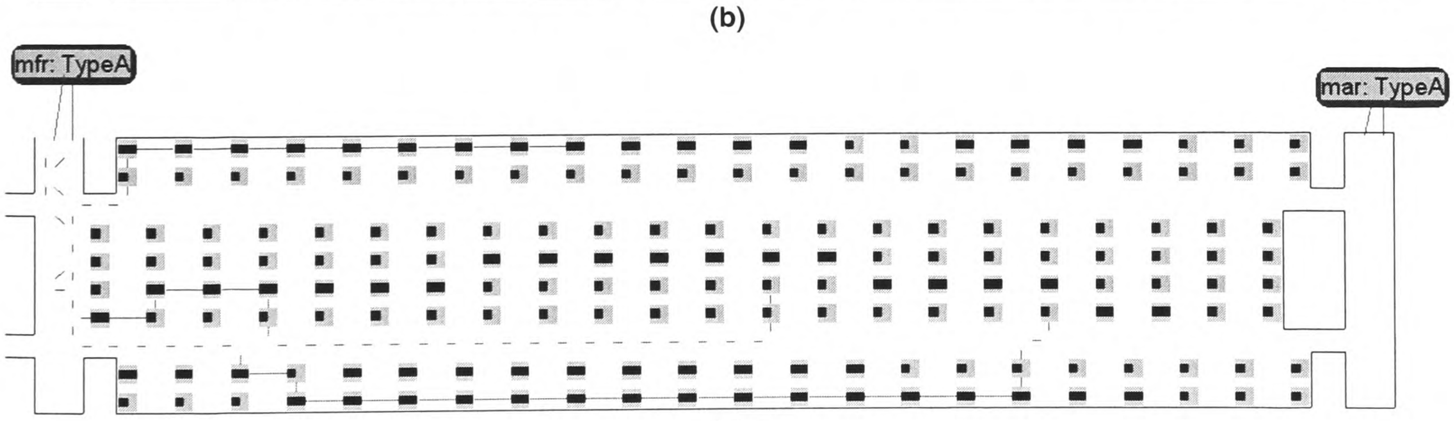
This scenario revisits aisle-swapping scenario 4 using the seat jumping algorithms. In this scenario there is **no smoke**. Examination of a single simulation demonstrates that passengers preferred where possible to climb ready collapsed seats and that in some instances they left aisles in order to climb over seating (see Figure 122).



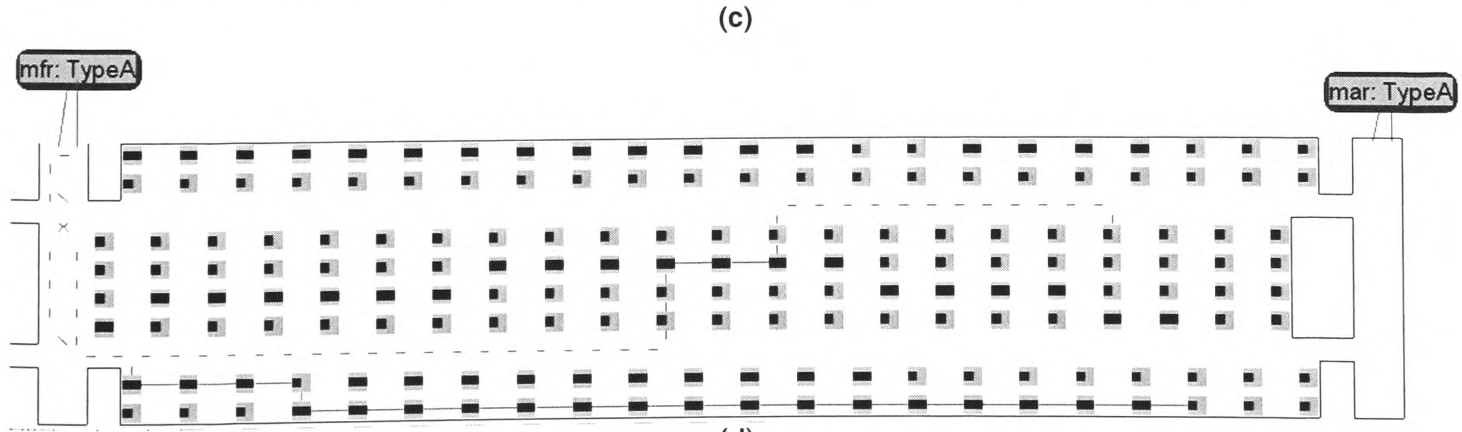
(a)



(b)



(c)



(d)

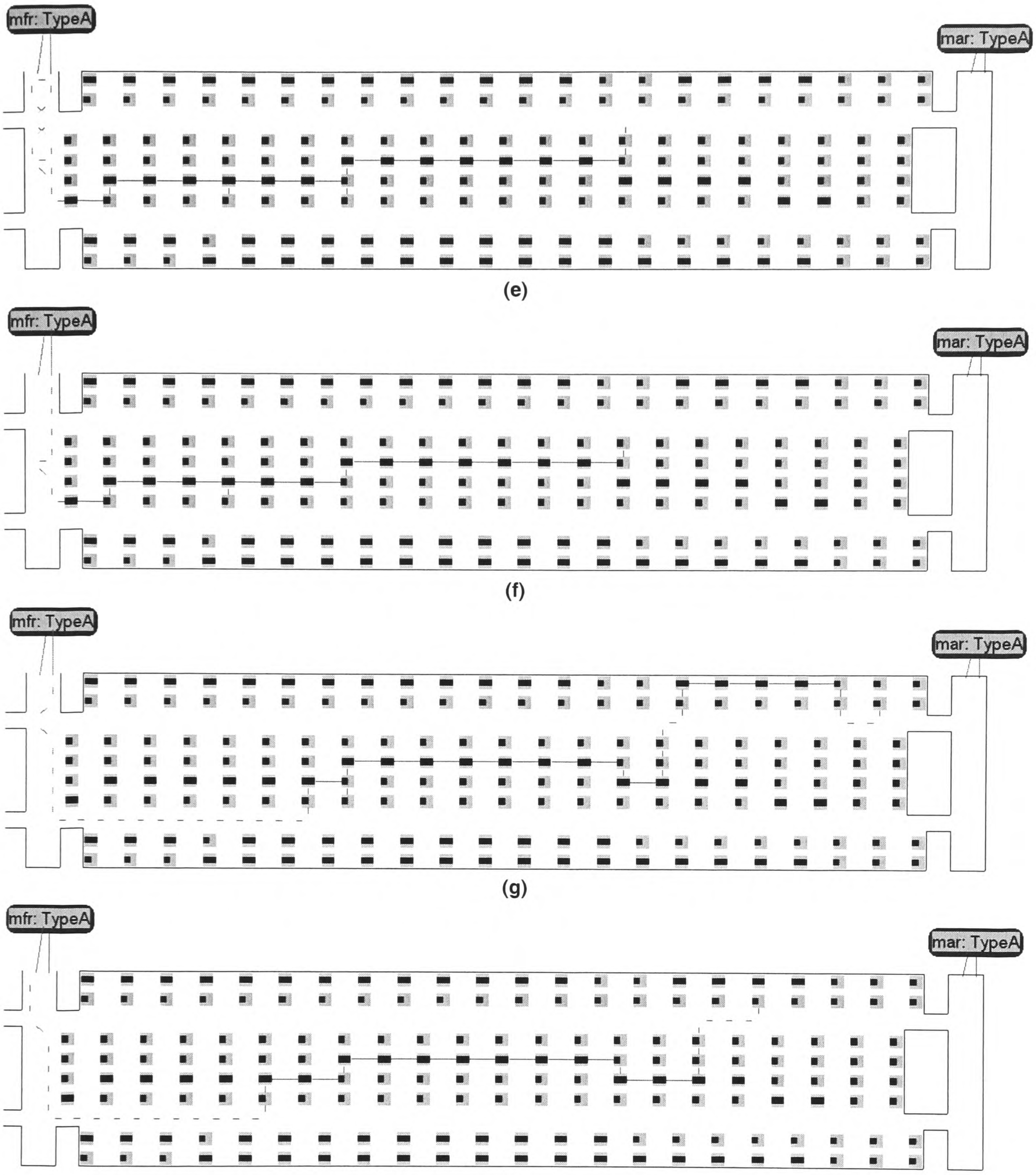


Figure 122: Paths taken by seat climbers in one simulation from scenario 2(a)

In this scenario on average 16 passengers climbed over seating and 23 swapped aisles (see Table 73). The average number of rows that passengers climbed was 10. This is much higher than the amount indicated in AASK V3.0. In part this originates from the somewhat artificial nature of the scenario in which passengers are unaffected by smoke. Althought it should however be noted that in one of the few accounts of seat climbing in wide bodied aircraft (the MD-11 at John F. Kennedy in 1995) a passenger climbed 13 rows of seating to reach the exit (see Section 5.4.5.3).

When considering seat climbing in wide-boidied aircraft it is apparent that there are actually longer distance to be travelled between exits than in narrow bodied airraft. As such passengers are given more oppourtunities to seat climb in wide-bodied aircraft. In addition data from AASK is limited for seat climbing in wide-bodied aircraft. Thus it is difficult to confirm the plausibility of the results in this instance. In reality fatigue effects may play a role in the number of seats passengers may climb in succession. There is however, no supporting data and the airEXODUS model does not currently poses the ability to model fatigue. A possible soluation could be to impose some arbitary cut-off on the maximum seats a passenger can climb based on the maximum found in AASK (i.e. 13 seat rows). However the data does not support this view. It would appear plausible that passengers could climb more than 13 seats - There is not fundamental barrier preventing passengers from climbing more than 13 seats.

Table 73: Summary of seat climbing scenario 2(a)

		TET (seconds)	PET (seconds)	CWT (seconds)T	Distance (seconds)	Aisle Swapped (pax)	Seat Climbed (pax)	Average No. Rows (Rows)
2(a)	Min	128.6	56.2	35.9	13.0	10	8	7
	Mean	142.9	59.0	38.8	13.2	23	16	10
	Max	169.5	62.5	42.3	13.4	32	25	13
	STDEV	9.8	1.5	1.5	0.1	7	4	1

4(a) Revisiting Aisle Swapping Scenario 4(a) (an elderly passenger in the far aisle) in severe emergency conditions with smoke concentration that increases to a specified level

This scenario models a developing smoke hazard. The hazard begins with an extinction coefficient of 0 and increases at a rate of 0.025 per second to a maximum extinction coefficient of 0.5. The maximum extinction coefficient of 0.5 is achieved after 20 seconds. An elderly passenger is present in the far aisle.

In this scenario on average 12 passengers elect to climbing seating. Most of these do so during the first 20 seconds of the evacuation however some climb seats after the maximum smoke density has been reached. It can be seen that the average number of seat rows that are climbed in this scenario is 5. This is much lower than the previous scenario and correlates better with the data from AASK. The reduction in the number of rows that passengers travel over seating results from the smoke hazard affecting passenger mobility. In these simulations as the smoke hazard develops passengers' mobility decreases until climbing over un-collapsed seats becomes too difficult. Thus some passengers that were seat climbing or may have considered seat climbing in future found themselves physically unable to and were forced to follow less difficult routes – possibly choosing to aisle swap instead. Some passengers with high agility were always able to climb over ready collapsed seating during the evacuation.

Table 74: Summary of seat climbing scenario 4(a)

		TET (seconds)	PET (seconds)	CWT (seconds)T	Distance (seconds)	Aisle Swapped (pax)	Seat Climbed (pax)	Average No. Rows (Rows)
4(a)	Min	127.0	54.3	34.0	13.0	16	6	2
	Mean	144.8	58.2	37.8	13.4	37	12	5
	Max	163.3	64.4	44.4	14.1	53	21	9
	STDEV	7.7	1.7	1.8	0.2	8	3	1

7.3.3 Concluding remarks

A method of simulating passenger aisle swapping and seat climbing have been developed based on the investigation of human behaviour in Chapter 5. The aisle swapping model distinguishes between aisle swapping in 90-second certification trial/non-fire/external fire conditions and severe emergency evacuations that involve fire and smoke. The seat climbing model is appropriate for use in severe emergency conditions, i.e. internal fire conditions, only.

The emphasis of the models is that passengers act on information they collect during their evacuation. Thus, in smoke conditions a mechanism of limiting their information is provided. The models are stochastic generating different results every time a simulation is run. The models are adaptive with passengers responding to the situation that they are faced and acting upon information that they receive.

The models can be run on wide-body and multi-aisle aircraft with any number of aisles. Finally, demonstrations of the aisle swapping model showed good correlation to the behaviours witnessed in 90-second certification trials. Further demonstrations showed the sensitivity of the models to environmental affects and the type of scenario.

8 Practical applications of evacuation modelling in the regulation, design of future aircraft and air accident investigation

8.1 Introduction

The final chapter of this thesis applies the techniques that have been developed in this work to various aviation applications. In doing so current and topical issues in aviation safety are addressed: namely aircraft safety regulation, design and accident investigation. The techniques developed in this work are applied to a current problem in each of these areas. Essentially this chapter asks and attempts to answer the question, *"What potential benefit do the techniques developed in this thesis provide to the safety community?"*

In the area of safety regulation, a current regulation and its assumptions are explored. Currently the prescriptive aircraft regulatory regime prescribes key characteristics and numerical thresholds on properties of cabin design. For example, exit widths, exit symmetry and (in wide-bodied aircraft) the requirement for cross-aisles to link the exits, *inter alia*. Whilst some of these rules are based on scientific research others, such as the maximum exit separation, are based soley on the opinions of experts and not on any underlying scientific understanding. The first application of the model is to investigate the factors that influence a key aircraft regulation, namely the maximum exit separation threshold requirement (i.e. FAR25.807 (f) (4)) [5] and the appropriateness of this influence. More specifically this study investigates the numerical value of the threshold, currently 60-feet in aircraft regulations, and examines the factors that may influence it. The study undertaken in this work represents the first publicly available assessment of this regulation.

In addition to providing understanding into regulations the techniques developed in this work also have the capability of being used in assess the performance of aircraft designs. Gaining understanding of the evacuation capabilities of aircraft during the design phase is extremely desirable as it allows safety assessments to be incorporated early in the design process. This is advantageous as issues associated with safety can become better intergrated into the design process rather than being considered as an 'extra' that is often attached once the design has been finalised. To understand the model's use in this context, the techniques developed in this work are applied to two future aircraft designs: namely a BWB (Blended Wing Body) and VLTA (Very Large Transport Aircraft). The model is used to simulate various evacuation scenarios in an attempt to provide an understanding of some of the key issues that these designs will face. Indeed these studies provide some initial insight into the critical geometric features that can impact upon the evacuation efficiency of these types of aircraft. Whilst only a small number of scenarios are investigated the model highlights areas of the designs that can be improved and areas that require further investigation. This study provides a demonstration of the type of issues in a design environment that could be addressed with these techniques.

Finally this chapter concludes by demonstrating the use of the techniques developed in this work in the area of accident investigation. The model offers accident investigators the oppourtunity to simulate previous accidents to better understand some of their causes. This type of application has already been demonstrated to great success with the use of aircraft fire models in the Swiss Air Accident investigation [177]. Here the concept if extended to evacuation simulation.

When used for accident investigation evacuation modelling is able to subject simulated passengers to life threatening situations involving fatalities – something physical experimentation could never undertake. To demonstrate this, the model is used to simulate a Manchester type accident scenario, i.e. a B737-236 in severe fire conditions. This investigation demonstrates how modelling can be used to understand human behaviour in real emergency situations and to some extent highlights the limitations of the current certification process in predicting or measuring aircraft performance in accident scenarios.

In conclusion this chapter will demonstrate the applicability of the techniques developed in this work to various segments of the aviation safety community.

8.2 A systematic study of a current aviation regulation using evacuation modelling techniques: "Is the 60 Foot Rule Relevant?"

As a demonstration of how aircraft evacuation simulation can be used in a regulatory context a study of a key aircraft regulation was undertaken for this thesis using evacuation modelling techniques. The study has been published in detail in refereed publications [36, 173, 174] therefore only the main points will be described in this thesis. The interested reader is referred to the Appendices for more a more detailed account of this study.

The regulation that was explored was recently in dispute by aircraft manufacturers and is the so-called "60-foot" rule. The rule appears in the FAR (i.e. 25.807 (f) (4)) [8] and there is an equivalent ruling in the JAR [5]. The FAR rule states;

"For an airplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage, as measured parallel to the airplane's longitudinal axis between the nearest exit edges." [8]

This regulation was introduced into the FAR as amendment 25-67. The origins of this amendment can be traced to a configuration modification to a B-747 aircraft. In 1984, Boeing Commercial Airplane Group (Boeing) requested certification for a modification to the B-747 that required a pair of exits on the main deck to be deactivated. This resulted in the maximum exit separation increasing from 44 feet to nearly 70 feet. In deactivating the pairs of exits, Boeing also reduced the maximum capacity of the main deck from 550 to 440 passengers in line with the regulations of the day.

Prior to this request and since 1967, the Federal Aviation Administration (FAA) had not specified a maximum exit separation. The FAA had however regulated through the FAR [9] that,

"...an exit be provided for every specified number of passengers, that an exit be located where it would allow the most effective means of passenger evacuation, and

that exits be distributed as uniformly as practicable taking into account passenger distribution." [9]

While the FAA granted the Boeing request, they received many complaints for allowing the deactivation of the exits. After much debate, the FAA introduced amendment 25-67 on June 16 1989 [9], setting an arbitrary limit of 60 feet to exit separation.

As with most prescriptive rules, amendment 25-67 suffers from the arbitrary nature of its specification. The rule is not founded on any fundamental understanding of evacuation dynamics, accident scenarios or human behaviour. The rule even ignores the nature of the exits (e.g. exit size) that exist at the end of the 60 foot separation.

8.2.1 Cabin and model configuration

The analysis focuses on a 'typical' cabin section of a wide-body aircraft that could be found located between two pairs of main deck Type-A exits (see Figure 123). The cabin section contained 220 passengers with passenger seating arranged in the 3-4-3 configuration. The initial cabin section has a door-to-door as measured from the centre of each door, of 18.1 metres or 59 ft 4 inches and conformed to the current FAR 25.807.(f)(4) requirements (see Figure 123). In addition a series of longitudinally stretched cabin sections with a door-to-door distance ranging from 60-390ft were generated in order determine the impact that exit separation had upon the evacuation performance of the cabin section.

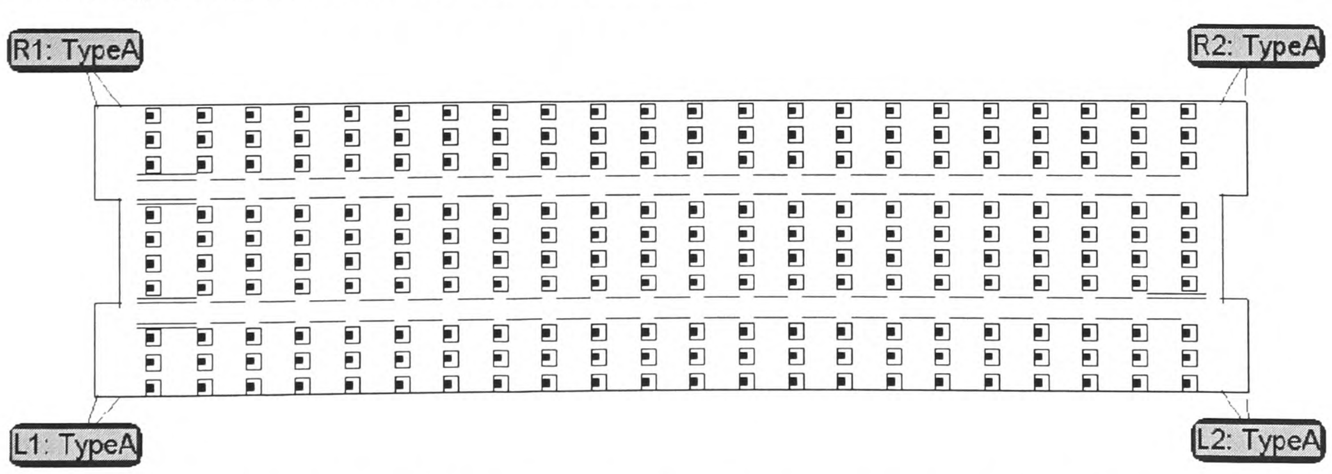


Figure 123: The airEXODUS representation of the base-case cabin section geometry

The model was configured using a standard 90-second population and using 'standard' 90-second certification behaviour. Essentially the behavioural options were similar to those used in the generalised validation scenarios described earlier in this work (see Section 4.3 for more details).

This study takes an incremental approach to its analysis starting with a very simply evacuation scenario case. As such none of the new functionality that was developed in Chapter 7 and 8 of this thesis employed. Instead, a very basic set of behavioural options were employed to establish base-case results. The next stage of this study would be to consider more complex scenarios, perhaps making use of the sophisticated capabilities developed in this thesis.

8.2.2 Results and discussion

Contrary to expectation this study found that for comparatively small exit separations, i.e. 60ft – 142ft) the total evacuation time of the aircraft remained approximately static (see Figure 124(c)). Indeed, whilst the time taken by passengers in travelling the extra distance to the exits was **increased** (see Figure 124(b)) it was being compensated for by passengers spending **less** time waiting in queues at the exits (see Figure 124(a)).

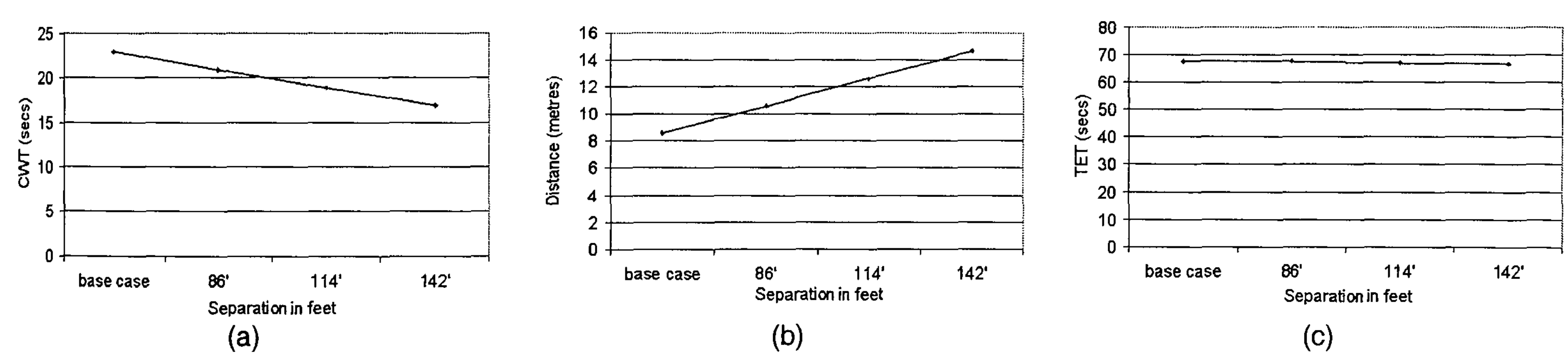


Figure 124: Results from scenarios S1 to S4 showing (a) the Average CWT, (b) the average travel Distance and (c) Total Evacuation Time as a function of exit separation

As the exit separation was increased beyond 142ft, so the congestion generated at the exits decreased still further, and the additional travel distance began to exert a direct influence over the total evacuation time (see Figure 125(a)). The full paper went on to reveal that a critical distance, 'the practical exit separation threshold' (see Appendix C [36]), exists for cabin sections. With exit separations below the critical distance the TET for the cabin section remained approximately constant regardless of the exit separation, whereas for exit separations larger than the critical distance, exit separation served to increase TETs. This resulted from the primary influence of evacuation time being congestion until the practical exit separation was reached.

Beyond the practical exit separation threshold the travel time to reach the exit was the primary influence of evacuation time. A subsidiary finding concerned passenger behaviour when travelling large distances through aircraft aisles. It was found that congestion occurred in aisles as queues developed behind slow moving passengers. This 'sub-queue congestion' meant that congestion never completely disappeared in the cabin section examined (see Figure 125(b)) irrespective of the exit separation distance.

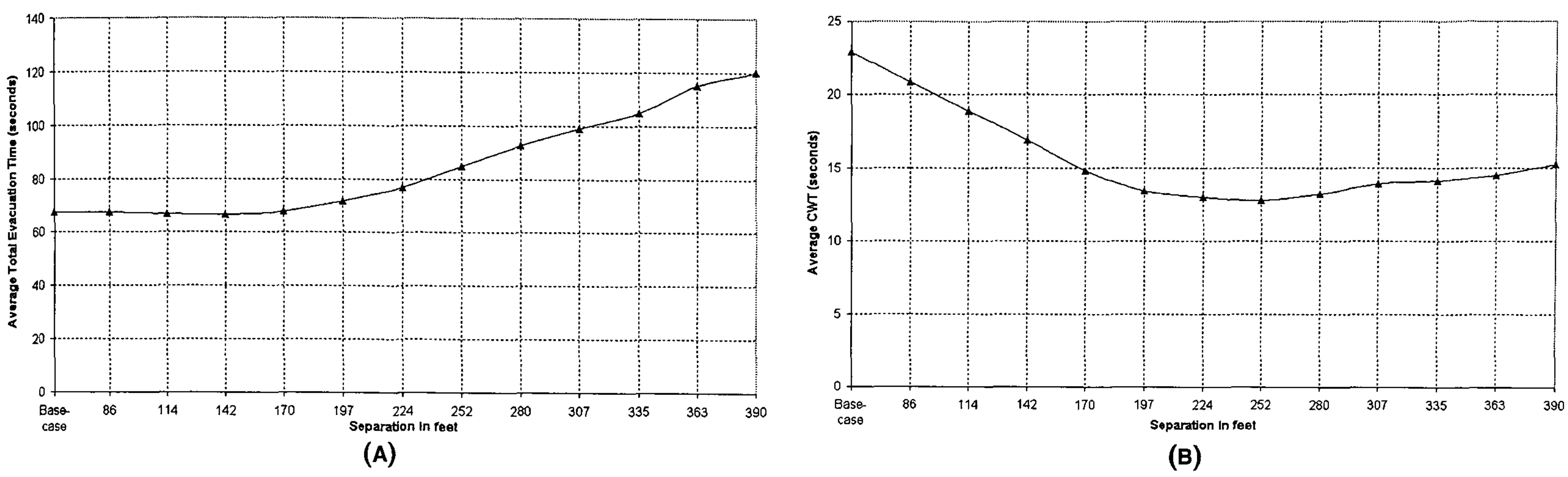


Figure 125: Results of the scenarios with mixed ability populations and an active exit on each side of the aircraft cabin. (a) TET as a function of exit separation and (b) CWT as a function of exit separation

To further understand factors that could influence the relationship between total evacuation time and exit separation, the set of simulations were repeated using different exit availability. Instead of disabling one exit from each exit pair (i.e. the R1 and R2), both exits from the rear pair were disabled and both exits from the forward pair were enabled (i.e. R1 and L1). This exit availability had the effect of increasing the distance that passengers had to travel at every exit separation (see Figure 126).

In these simulations it was found that the practical exit separation threshold was decreased from approximately 170 feet to 114 feet (see Figure 127). The practical exit separation threshold is therefore shown to be sensitive to the nature of the scenario to which it applies.

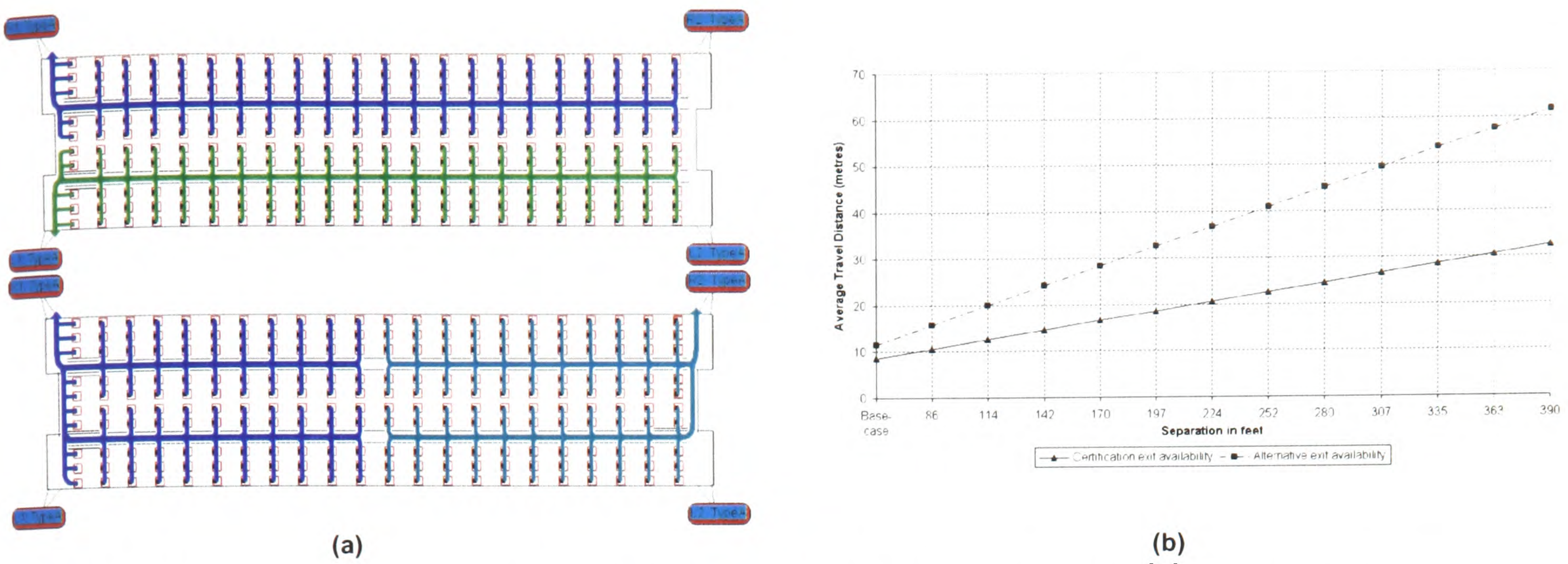


Figure 126 (a) The predicted path of movement for the two exit configurations examined namely, (top) the alternative exit configuration with the aft exit pair inoperable and (bottom) the standard configuration with one exit from each exit pair inoperable and (b) the average travel distance of passengers for each exit availability

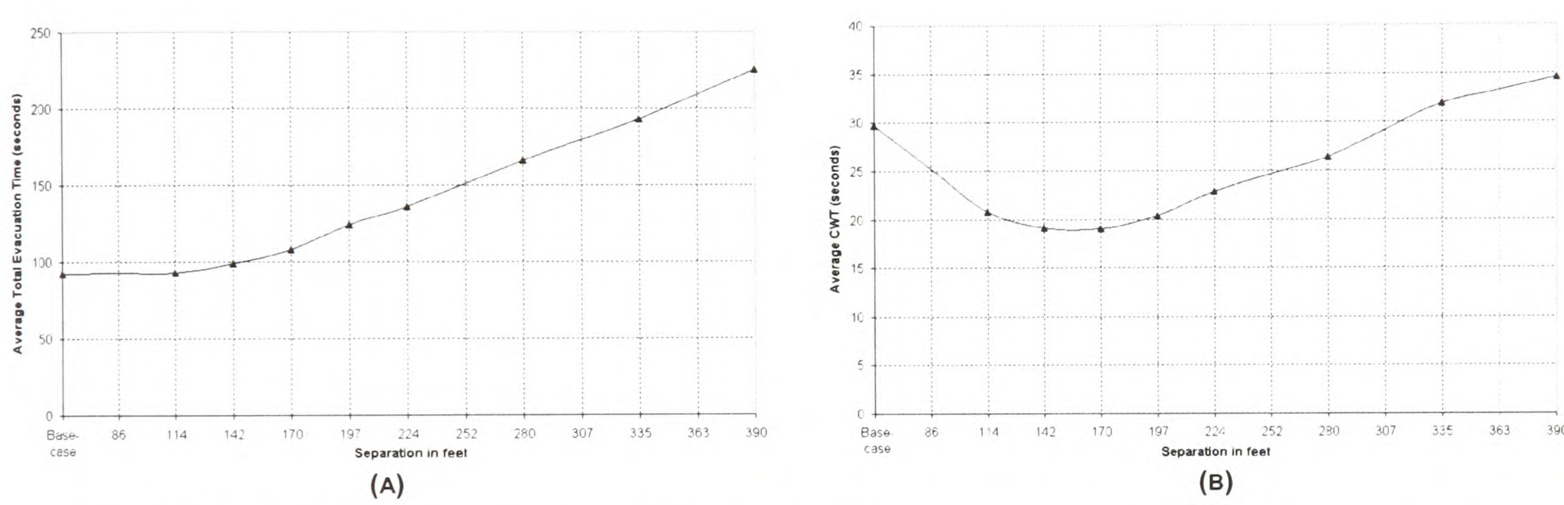


Figure 127: Results of the scenarios with mixed ability populations and two forward active exits. (a) TET as a function of exit separation and (b) CWT as a function of exit separation

8.2.3 Main findings

Numerous new findings concerning this regulation were revealed during this study (see Appendix C [36]). A main finding of this work was that for the population and cabin section investigated and under certification conditions, exit separations of **60** to **170** feet will result in approximately uniform averages of total evacuation times and personal evacuation times. This suggests that with this cabin section under these conditions, an exit separation of **170** feet is the **'practical exit separation threshold'** for Type-A exits that cannot be exceeded without an adverse effect on evacuation times.

Another significant finding of this study concerns the influence of exit availability on the **'practical exit separation threshold'**. If certification conditions are maintained with the exception that both exits from an exit pair are available while no exits from the alternative exit pair are available, the **'practical exit separation threshold'** (which in this case relates to the length of the cabin section) for this cabin section is decreased to **114** feet. This is due to the additional distance that must be travelled for a given exit separation in this configuration compared with the previous configuration. This suggests that the practical exit separation threshold is strongly dependent on which combination of 50% of the exits are selected i.e. the nature of the scenario.

In addition, it was noted that having two exits in an exit pair available results in a decreased exit flow rate compared with the previous configuration. It is suggested that if an exit has a reduced exit flow rate capability, the practical exit separation threshold is increased, thus exit flow rate capability is an important factor in determining maximum exit separation.

Indeed this study (see Appendix C [36]) indicated that numerous factors such as exit flow rates and exit availability all exert a *strong* influence on the critical exit separations [36]. By implication, the **number of passengers** located between the two exits is also an important parameter. While not explicitly considered, it is expected that if the number of passengers between the exits were greatly reduced, thereby reducing the levels of congestion, this would have the effect of greatly reducing the ***practical exit separation threshold.*** If correct, this has major implications, as it suggests that the "worst case scenario" from an exit separation view occurs not when the maximum number of passengers are considered but when fewer passengers are considered.

The results of this work suggests that it is not advisable to mandate a maximum exit separation without taking into consideration exit availability, exit type, occupancy load and aircraft configuration. This has implications when determining maximum allowable exit separations for wide and narrow body aircraft. It is also relevant when considering the maximum allowable separation between different exit types on a given aircraft configuration.

This work also suggested that from the view of evacuation efficiency under certification conditions, most 'practical' exit separations beyond 60 feet (i.e. < 170 feet) are not expected to influence the evacuation time. This is not to say that in designing a "safe" aircraft it is acceptable to have exit separations greater than 60 feet.

Other factors apart from evacuation time under the current FAR 25.803 evacuation scenario should be considered when determining maximum exit separations. For instance, passenger disability, the presence of fire and smoke, the orientation of the aircraft, reduced passenger numbers in addition to the parameters already identified are important parameters that need to be taken into consideration. Indeed, severe accidents smoke and fire could slow the travel speeds of passengers whilst impact damage could reduce the number of passengers that are evacuating. In this scenario the maximum exit separation threshold could well be below 60 feet. To correctly take all these factors into consideration when designing and approving new aircraft types requires a performance based regulatory environment that takes a holistic view of safety rather than the existing prescriptive environment.

Finally, this work demonstrated how the rationale and relevance of aircraft regulations can be examined using the techniques explored in this thesis. Indeed the study revealed a large amount of new understanding about this particular regulation and in doing so the potential benefit to regulators of evacuation modelling was clearly demonstrated.

8.3 Exploration of future evacuation design and regulation issues using evacuation modelling techniques: "An assessment of the evacuation performance of VLTA and BWB aircraft"

The previous section explored how evaluation modelling can be used to provide insight into current aviation regulations. This section describes the results of two studies using aircraft evacuation modelling in a design context. Two new types of aircraft are used to demonstrate the technology developed within this thesis, namely VLTA (Very Large Transport Aircraft) and BWB (Blended Wing Bodied) aircraft.

VLTA were selected as they pose considerable challenges to designers, operators and certification authorities. VLTA designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two parallel aisles and two full-length passenger decks. The drive for increased efficiency, passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number, location and type of exits, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed.

The second new type of aircraft examined – the BWB - represents and even more radical departure from current aircraft design. Indeed should the BWB aircraft become a reality, designers will be faced with numerous questions with unknown answers. For example, should continuous solid cabin partitions be used along the length of the aircraft? Should these cabins have cross aisles linking each cabin section? Will it be sufficient to simply have exits in the forward and aft sections of the aircraft? Can the largest exits currently available cope with passenger flow arising from four or five main aisles? Do we need to consider new concepts in exit design, perhaps introducing three or four lane exits? How efficient can a three or four lane exit be in evacuating passengers? Should the main aisles be made wider to accommodate more passengers? How much time is actually required for safe egress from a BWB aircraft? Does the 90-seconds concept have any relevance to VLTA and BWB aircraft? The second study demonstrates how evacuation modelling technology can be used to address some of these questions.

This section describes the results of a study into the evacuation efficiency of both types of aircraft. Again, this work has been accepted for publication in refereed scientific literature [169] and so only the main points will be discussed within this thesis. A more detailed account of these studies can be found the Appendices of this thesis.

8.3.1 The use of evacuation modelling in the design of VLTA

In order to demonstrate the use of the model a hypothetical two deck aircraft cabin has been designed. The aircraft had two decks and a capacity of 580 passengers in a three-class configuration. The upper deck seated 236 passengers in first and business class while the lower deck seats 344 passengers in first and economy class (see Figure 128). The aircraft had nine pairs of Type A exits, four on the upper deck and five on the lower deck. A staircase was positioned towards the front of the aircraft so as to assist in the expeditious boarding and disembarking of passengers. The staircase had dimensions typical of that found in buildings. Within airEXODUS, the behaviour of the passengers on the staircase is based on that found in buildings, where the speed of passengers is dependent on the age and gender of the passenger and whether they are travelling up or down the stair. The cabin was populated using standard features within the model commensurate with FAR requirements for certification testing [12].

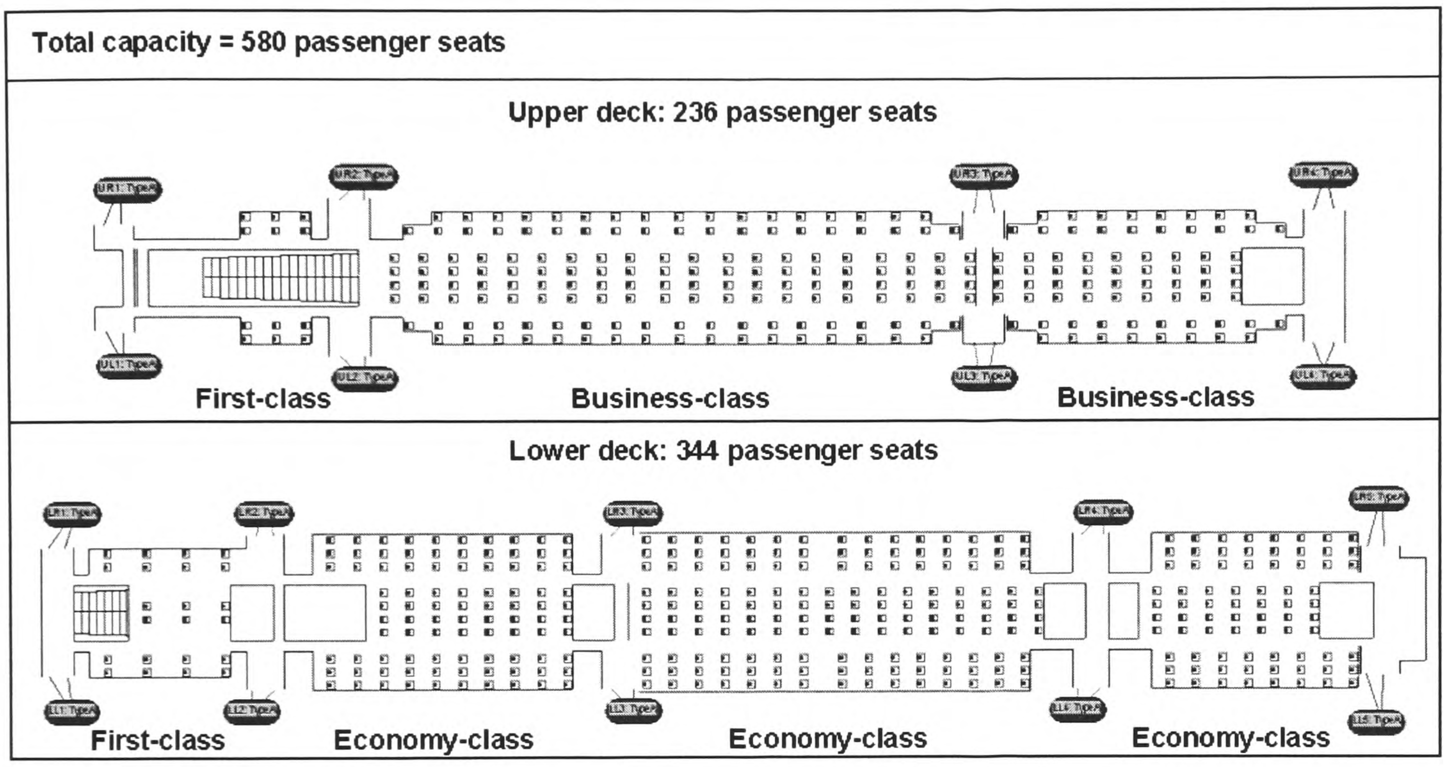


Figure 128: A schematic of the UOGXXX VLTA

Numerous scenarios were investigated covering a range of evacuation scenarios, from 90-second certification trials to total exit availability. Only the results of one set of scenarios are discussed here. These were determined sufficient to demonstrate the potential benefit to aircraft design from using evacuation modelling technology. Further details can be obtained elsewhere [169].

During the study a precautionary evacuation scenario in which only the lower deck exits were available was simulated. In this scenario ALL of the upper deck passengers were forced to descend the staircase to reach lower deck exits. It was found that when passengers were forced to use the internal staircase to access the exits on the lower deck, the evacuation time increased dramatically beyond the 90-second certification requirement to an average of **149** [143.7-158.6] seconds (see Figure 129). Furthermore, in this scenario, all of the airEXODUS simulations were in excess of the 90-second certification trial testing requirement (see Figure 129). The challenge was to ascertain if any configurational and/or procedural modifications could bring these evacuations below 90-seconds. During the course of this analysis the cabin crew redirection models developed in this thesis were used.

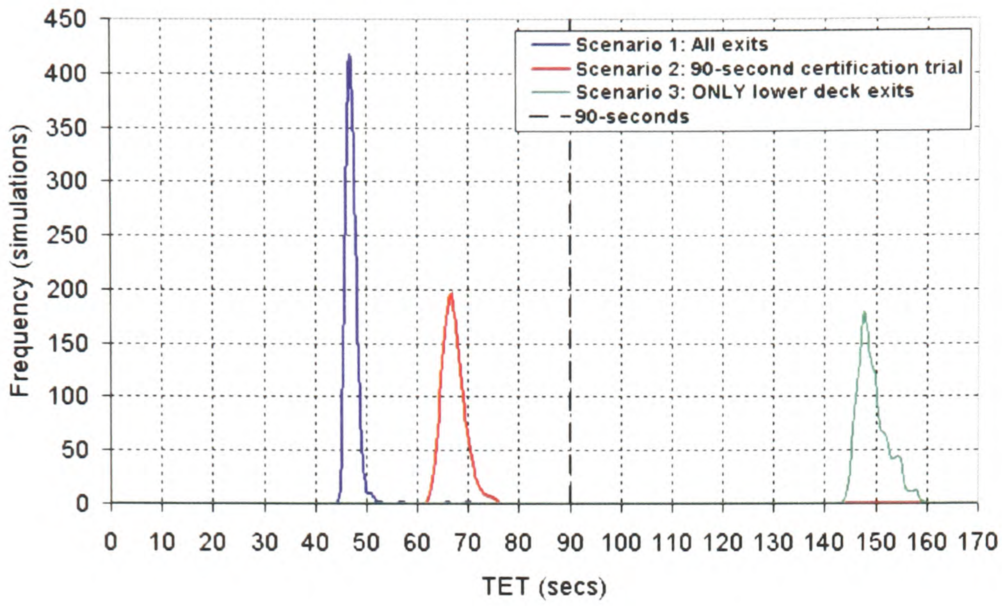


Figure 129: airEXODUS generated TET frequency distribution for scenarios 1, 2 and 3a

In an effort to achieve this, the real time animation output from airEXODUS was scrutinized to understand the dynamics of this scenario. Figure 130 depicts a frame from this animation at **48** seconds. This suggested that after **48** seconds the only passengers remaining on the aircraft are from the upper deck. In addition, the graphics indicated that these passengers were forced to queue in the aisles of the upper deck whilst waiting to descend the staircase. Closer examination of Figure 130 revealed that the cross-aisle area at the foot of the staircase was sparsely populated (the dashed circle in Figure 130) in contrast to the densely populated reservoir at the top of the staircase (the solid circle in Figure 130). Furthermore, Figure 130 reveals that the staircase – represented by the vertical columns to the left of the diagram - were full of passengers. This lead to the conclusion that the width of the staircase was contributing to the bottleneck and forcing passengers to queue on the upper deck.

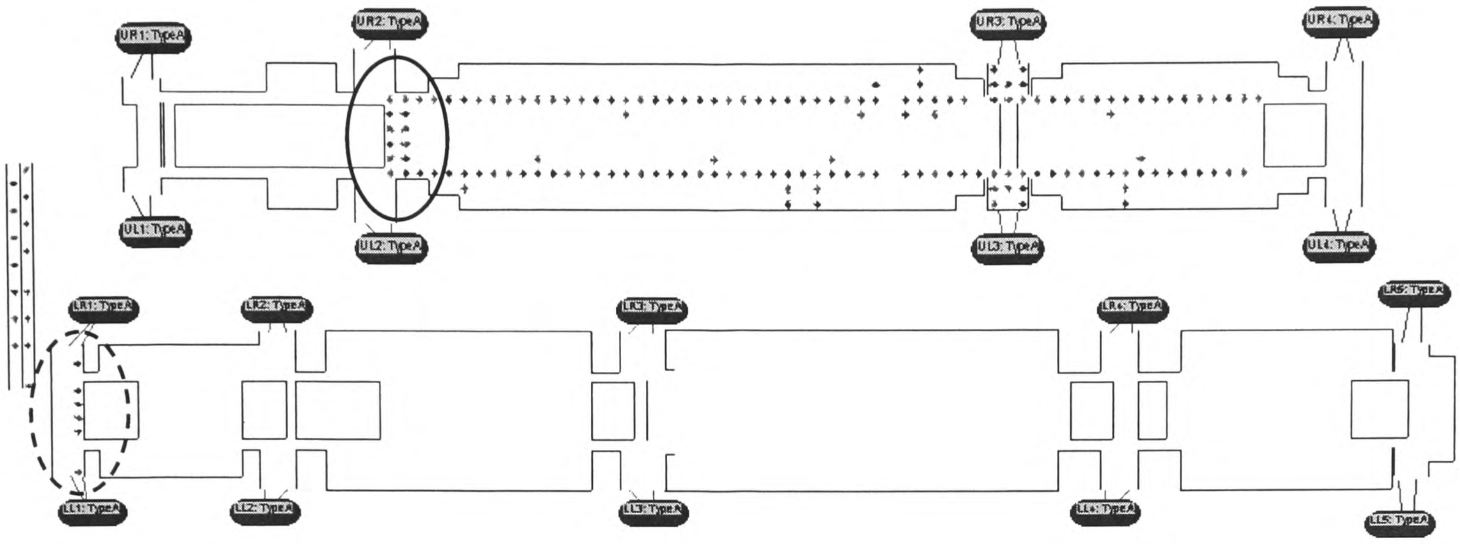


Figure 130: Graphic output from airEXODUS showing congestion at the top of the stairs 48 seconds after the start of the evacuation

It was asserted that in a balanced escape system all of the components within the evacuation system must have equivalent flow rates to avoid the generation of 'bottlenecks'. It was suggested that the flow rate down the stairs was less than the supply rate from the aisles creating a bottleneck at the head of the stairs and that the discharge capacity of the stairs was less than the discharge capacity of the exits resulting in the under utilised exits.

Indeed from the study of video footage from past certification trials, the flow rate normally achieved through main cabin aisles is approximately 77.4 people/minute [158]. Under similar conditions, airEXODUS produces an average flow rates with an average of approximately 74 people/minute. In addition, the flow rate capacity for a standard stair as specified in the UK Building Code [163] is 80 people/minute/unit width. As the staircase was fed by two aisles, each with an average flow rate capability of approximately 74 people/minute, the net flow rate into the stairs is potentially 148 people/minute, whilst the stair capacity is approximately 80 people/minute. These calculations suggested that the stairs were unable to cope with this flow and a bottleneck developed at the head of the stairs. This hypothesis was tested via improving the exit capacity at the base of the stairs, i.e. by demonstrating that increasing the flow rate of the exits would have no effect. This was accomplished using the cabin crew redirection models developed earlier in this thesis.

Using the cabin crew redirection models developed in this work. Two cabin crew were assigned duty stations on the lower deck by the bottom of the stairs. Each was given the task of optimising the evacuation via redirecting passengers to adjacent exits. This meant that the crewmember on the left of the aircraft could assign passengers to use doors L1 and L2, while the crewmember on the right of the aircraft could assign passengers to doors R1 and R2 (see Figure 131).

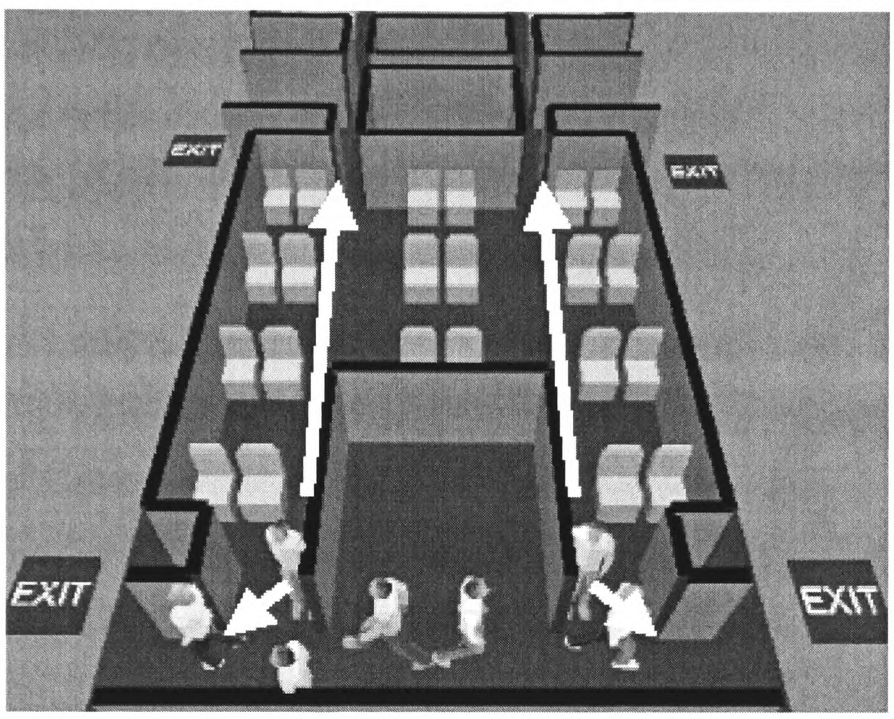


Figure 131: Example of crew exit responsibilities

In these simulations the cabin crew redirection algorithms were configured to perform in an optimal manner. This was done to remove crew performance as a variable in the study - when using an optimal crew performance we are able to determine if any benefit is possible. To facilitate this, the crew were considered to have complete knowledge of all the factors required to make perfect redirection decisions. Furthermore, the passengers are considered to be compliant. When this scenario was run the simulated crew redirected very few passengers to alternative exits as they determined that there would be no net benefit to the evacuation of the aircraft. The application of crew procedures did not improve the evacuation time of the aircraft. This supported the notion that the stairs were acting as a bottleneck.

In this example the crew redirection algorithms generated a negative result. The lack of redirection does not indicate a failure in the algorithms, rather the failure of the crew redirection procedures as deployed on the aircraft configuration. In this study the crew redirection algorithms serve their purpose in delivering a negative answer to the question, *"Can crew procedures speed the evacuation of this aircraft configuration under these conditions?"*

A further set of simulations were performed in which the stair width was incrementally widened. Whilst initially the wider stairs expedited the evacuation of the aircraft, the TET formed a plateau (see Figure 132 (a)) as the number of stair lanes was incremented beyond three. Again crew procedures were applied at the base of the stairs but were found to have little effect on the total evacuation times of the simulations (see Figure 132(b)). As before, the crew redirection algorithms provided a negative answer. Again, this does not reflect a failure in the algorithms but rather a failure in the procedure as currently employed on this aircraft.

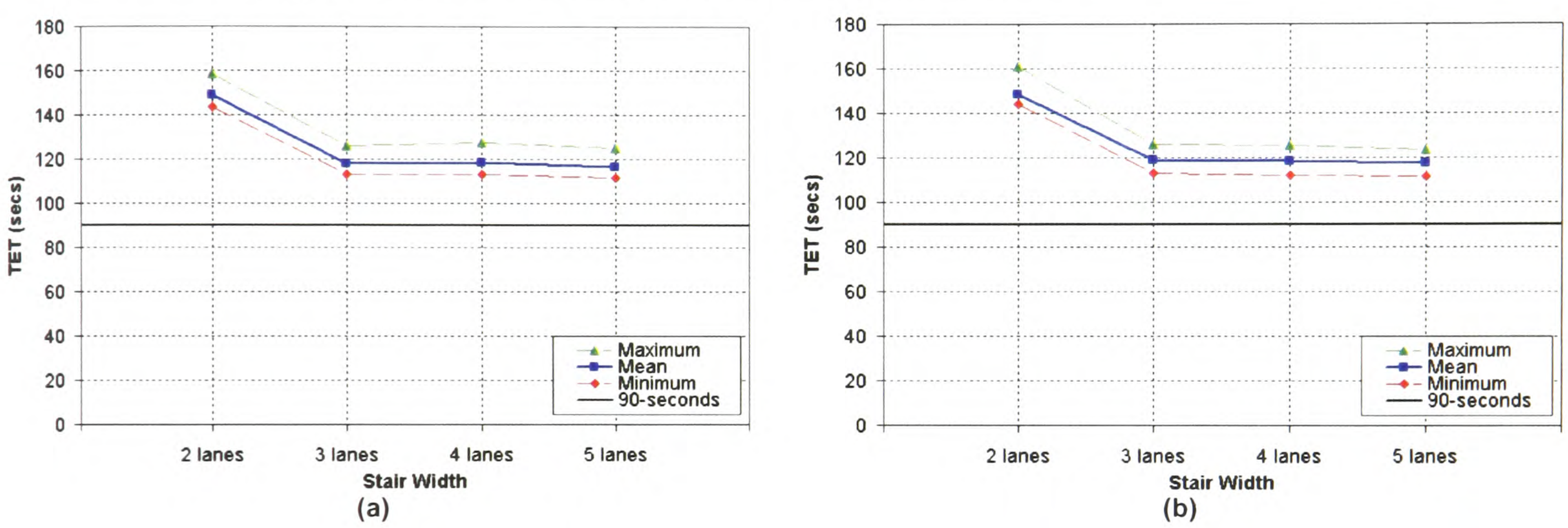


Figure 132: TET as a function of stair lane width (Scenario 3d), (a) without cabin crew management and (b) with cabin crew management

The graphics generated by airEXODUS (see Figure 133) again indicated that the exit vestibule at the base of the staircase was rarely fully packed (the dashed circle in Figure 133). Consequently, the adjacent R1 and L1 Type-A exits were not operating to their full capacity in any of the cases thus far discussed.

Since increases in stair flow capacity (i.e. stair lanes) had little effect, the bottleneck (as indicated by the plateau) must originate from the supply capacity at the top of the stairs. This hypothesis was again strengthened through examination of the real time airEXODUS graphical output (see Figure 133). It was apparent from the graphical output that the population density immediately adjacent to the top of the staircase was low (the solid circle in Figure 133) in the four and five lane staircase scenarios. In addition, some sub-queues developed within the upper deck aisles (see Figure 133).

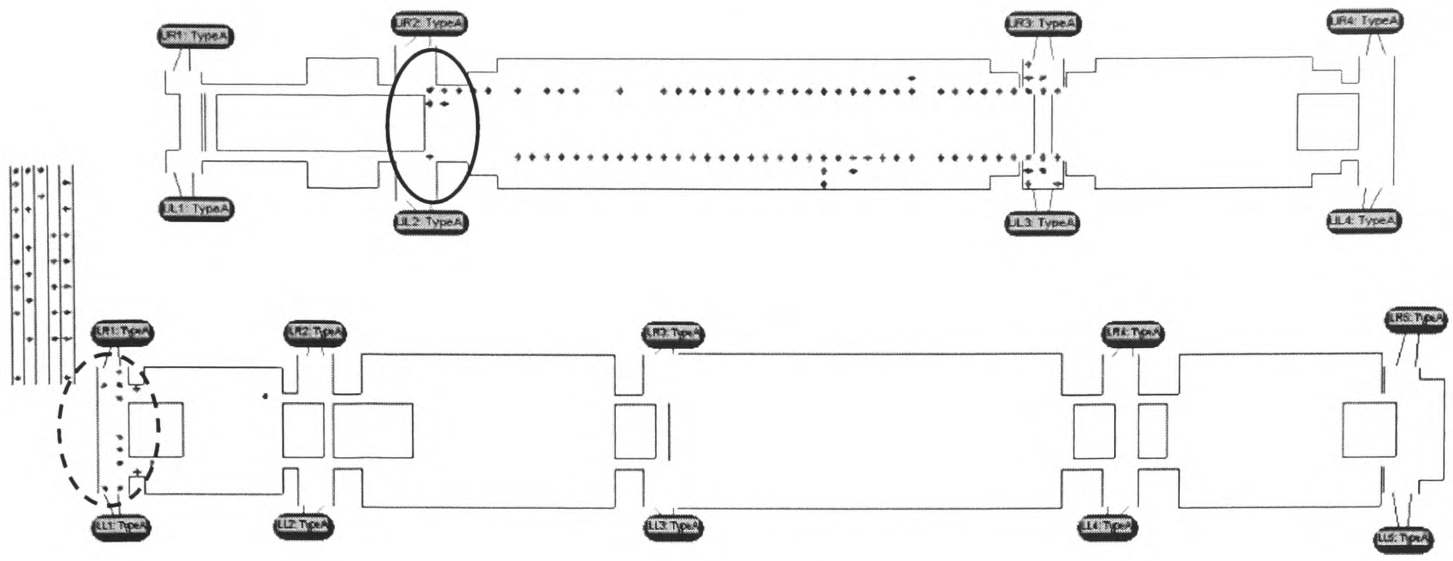


Figure 133: Graphic output from airEXODUS with a 2-lane exit staircase at 55 seconds with cabin crew management

A method of increasing the supply capacity at the top of the stairs was proposed that involved having stairs located centrally within the aircraft cabin. This had the effect of generating forward and aft aisle flows into the staircase (see Figure 134). In addition locating the stairs centrally would reduce the travel distance of the upper deck passengers and thus reduce sub-queue effects.

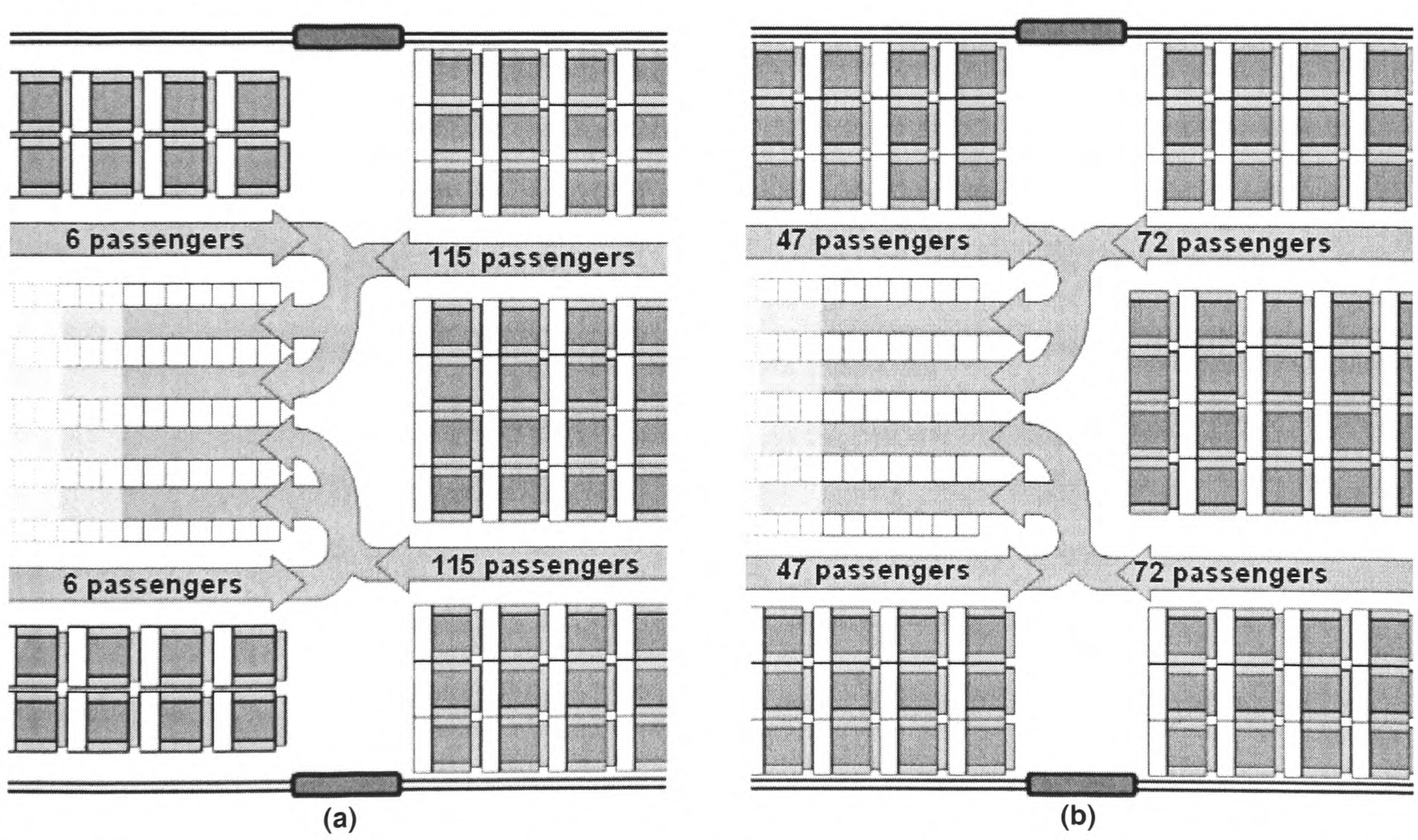


Figure 134: The number of passenger that would use forward and aft moving passenger aisle for (a) the original design and (b) the alternative design

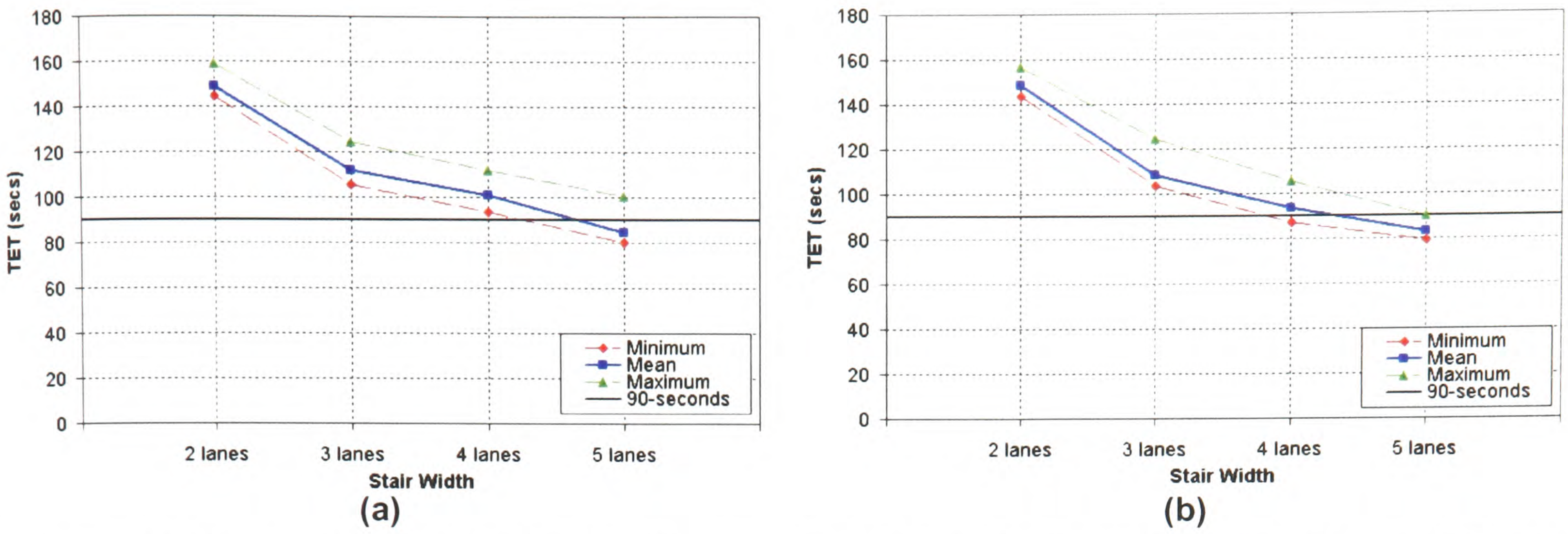


Figure 135: TET as a function of stair lane width for the alternative design (Scenario 3e) (a) without ACCM (b) with intelligent ACCM

The centrally located staircase was found to improve the evacuation times in the desired manner (see Figure 135(a)). Furthermore, the alternative design was amenable to procedural improvement. As before this was demonstrated via simulations in which 2 crew members were configured to perform optimally and given responsibility for managing the flow of passengers between lower deck exits. With the widened and relocated stairs the crew redirection algorithms delivered a positive result and improved the evacuation efficiency of the aircraft. With the new design the same crew procedures that generated a negative result previously began to have an impact on evacuation performance. It can be seen that when employing crew redirection procedures at the base of the stairs the majority of passengers evacuated in under 90-seconds (see Figure 136).

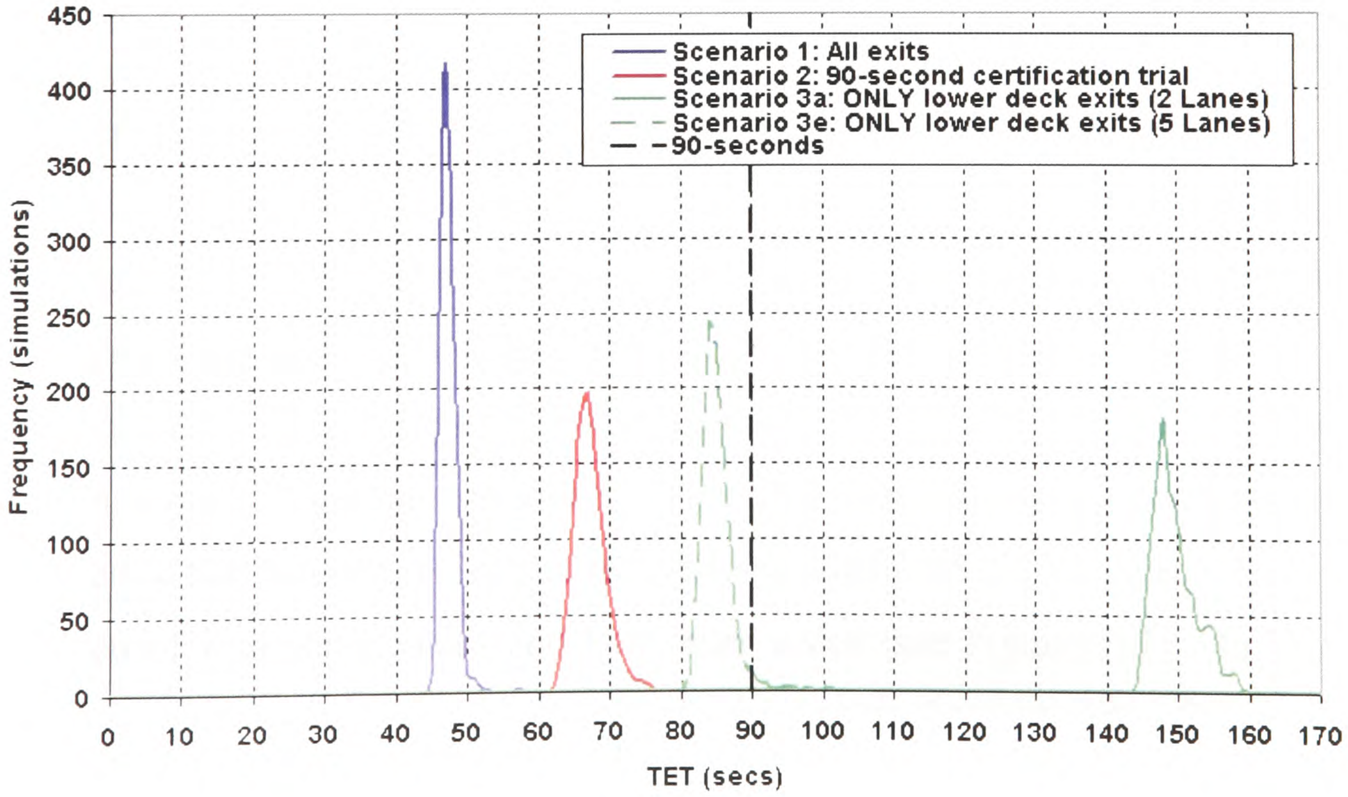


Figure 136: airEXODUS generated TET frequency distribution for scenarios 1, 2, 3a and 3e (with five lanes)

This work demonstrated how design and procedural aspects of future aircraft design could be evaluated using evacuation modelling technology. Indeed, without the use of evacuation modelling technology numerous physical experiments would have had to be performed, which would be extremely expensive, time consuming and subject volunteers to risk of injury. Using evacuation modelling technology designs were tested quickly, relatively cheaply and safely.

This study also demonstrated the use of the cabin crew redirection algorithms developed in this thesis to a real evacuation application. In this study the algorithms demonstrated both negative and positive answers to the question, *"Can crew procedures improve the evacuation efficiency of a particular aircraft configuration/scenario?"* In this study a negative answer indicated that the crew procedures being tested would have no effect on evacuation efficiency whereas a positive answer indicated that they will.

8.3.2 Examining BWB evacuation performance

In the second future aircraft design demonstration a BWB aircraft was evaluated. Early designs of BWB aircraft assumed that you evacuate passengers successfully via aft exits. This study performs and investigation of this area using the techniques developed in this work.

In this study three alternative designs were considered corresponding to the rear end of the aircraft. The first section modelled consisted of 420 passengers located in five rows seated 3,5,5,5,3 abreast (Scenario 1 in this section). This section consisted of four inner main passenger aisles. The second section (Scenario 2 in this section) consisted of the same number of passengers and seating configuration however two additional outer aisles are provided. The final case (Scenario 3 in this section) consisted of 500 passengers located in five rows seated 5,5,5,5,5 abreast. This section consisted of four inner aisles and two outer aisles (see Figure 137). In all cases, passengers were seated no more than three seats away from an aisle. The four inner aisles feed directly into the four rear Type A exits. A forth scenario in this section evaluates configuration 3 under different exit availability conditions (explained later).

The forth scenario was modelled under non-severe emergency condtions. As such the aisle swapping algorithms were activated as was the passenger redirection models.

In all of these scenarios the seat pitches of each design were identical (30 inches) as were the aisle widths (20 inches). At the rear of each cabin section was a large unobstructed cross aisle 2m deep. Also located at the rear of the cabin section were four Type-A exits. The model made use of the standard exit hesitation time distribution for assertive cabin crew and Type-A exits. The exits were unobstructed by monuments in the vicinity of the exits so that a clear view can be obtained of all exits. As the section examined only represented a portion of the aircraft geometry, it was implicitly assumed that the aircraft had additional seating capacity and additional exits towards the forward of the aircraft. The passenger populations were specified as described previously and all exits were assumed to be opened and ready for use after 11.1 seconds.

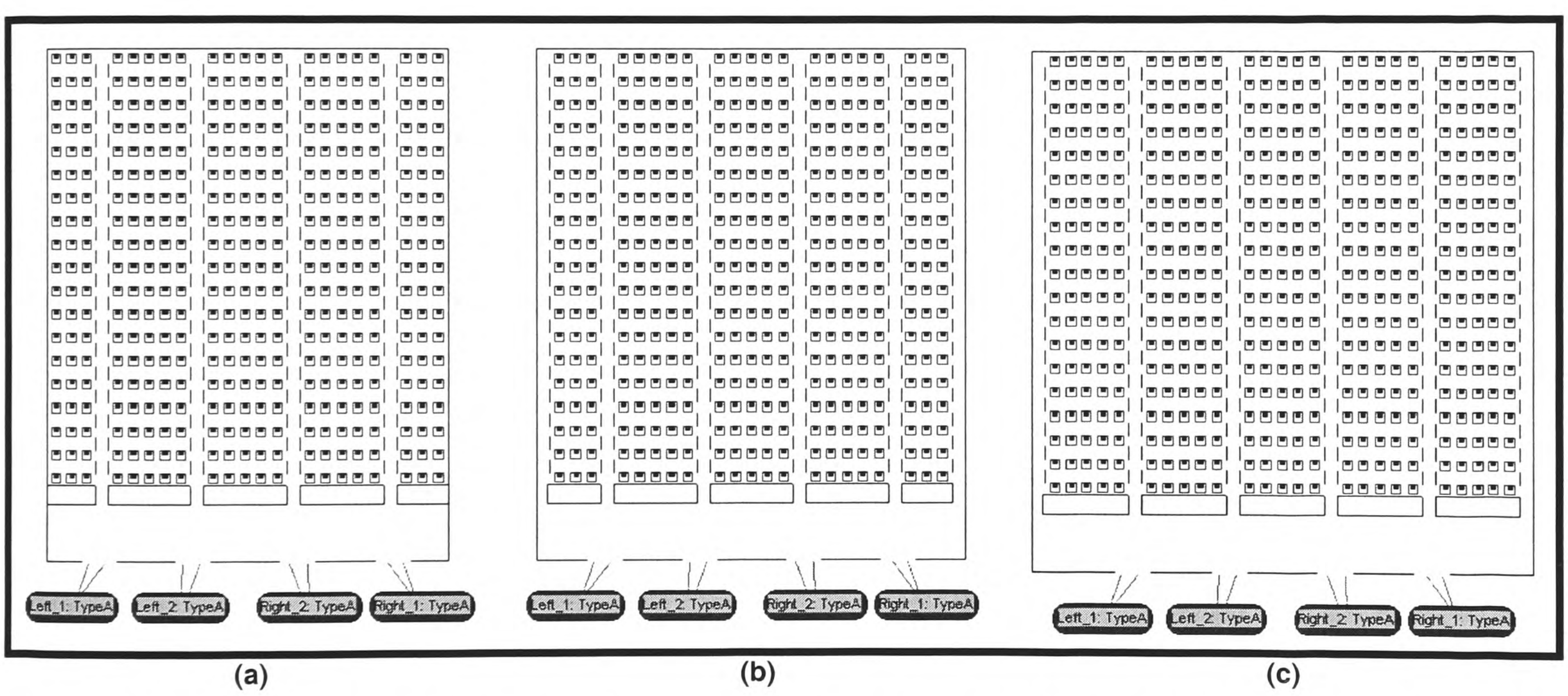


Figure 137: Three different BWB test sections represented within airEXODUS. The three sections consist of (a) a seating configuration of 3-5-5-5-3 with 420 passengers, (b) a seating configuration of 3-5-5-5-3 with perimeter aisles also seating 420 passengers and (c) a seating configuration of 5-5-5-5-5 with perimeter aisles seating 500 passengers

8.3.2.1 Scenarios 1,2 and 3: BWB Evacuation Performance

In a conventional aircraft, the passenger load represented by Scenarios 1 and 2 would easily be accommodated in an aircraft with four pairs of Type-A exits. In such a conventional aircraft four exits would be used for the certification trial and the aircraft would be expected to produce a sub 90-second certification evacuation performance.

Table 75: Overall airEXODUS statistics for the three BWB cabin layouts

Scenario	Overall statistics					
	Pax	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS
1	420	92 [85.5-99.9]	27.8 [26.4-29.2]	11.3 [11.2-11.5]	45.3 [43.7-46.6]	0.09 [0.02-0.17]
2	420	73.4 [68.9-80.7]	18.5 [17.4-20]	12.6 [12.2-12.9]	37.6 [36.2-39.4]	0.08 [0.01-0.18]
3	500	81.8 [77.4-88.1]	22.5 [21.3-24.2]	13.4 [13-13.7]	42.5 [41.1-44.4]	0.08 [0.01-0.17]

In Scenario 1 it was found that the average total evacuation time was in excess of 90-seconds (see Table 75). The results suggested that while the exits were reasonably well balanced (OPS<0.1), the exit flow rates were sub-optimal. In effect, the exits were being under utilized as the four main cabin aisles could not supply sufficient passengers to keep the four Type-A exits working at full-capacity. It was noted from the airEXODUS real time animation output (see for example Figure 138) that the cross aisle at the rear of the aircraft was never fully packed with passengers. In an attempt to improve the passenger flow to the exits two additional aisles were added to the aircraft (Scenario 2) and the simulation repeated. In this situation the total evacuation time greatly decreased to an average of **73.4** seconds, thus satisfying the 90-seconds requirement. In this case the cumulative wait time (CWT) associated with congestion also significantly decreased (see Table 75). Furthermore, the exit flow rates for each exit have increased and were close to their maximum practical average values.

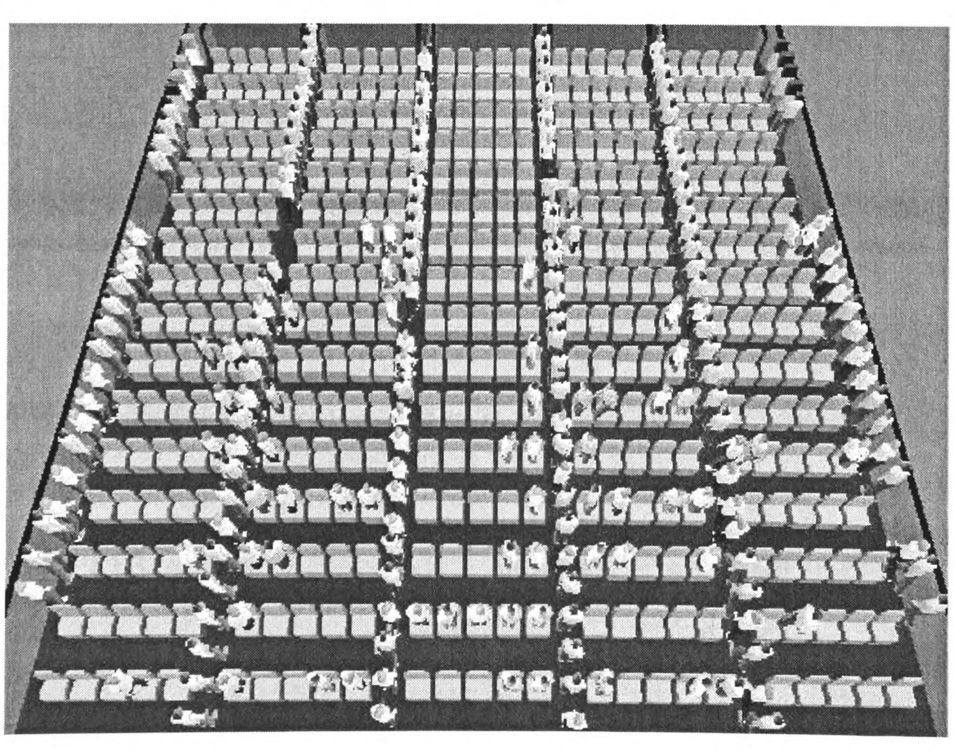


Figure 138: vrEXODUS generated scene from airEXODUS simulation of BWB evacuation simulation.

As the evacuation time had decreased significantly through the introduction of the outer aisles, it was suggested that it may be possible to increase the passenger load that can be serviced by the existing exits. In Scenario 3 the passenger load was increased to 500 through the addition of two additional seat rows to the outer rows. In this case the average total evacuation time increased to 81.8 seconds, still satisfying the 90-second requirement. It was noted that in this case the average CWT has increased compared with the previous case reflecting the increased congestion experienced throughout the aircraft.

In a final case (Scenario 4), the Right 1 and Right 2 exits from Scenario 3 were made inoperable throughout the scenario whilst all other factors remained similar to scenarios 1-3. In Scenario 4 the passengers were therefore forced to redirect to doors Left 1 and Left 2. In addition, the passengers were modelled as if they were in a non-severe accident using the passenger decision making models developed within this thesis. Furthermore, this scenario made use of the aisle swapping behaviours also developed within this thesis – seat climbing behaviour was however excluded from the scenario.

Table 76: BWB evacuation with R1 and R2 closed

		L1			L2	
	PAX	TET sec	Flow rate pax/min	PAX	TET Sec	Flow rate pax/min
Minimum	203	134.4	83.3	264	142.8	102.8
Average	217	148.7	92.1	283	151.7	115.9
Maximum	236	163.5	106.7	297	165.8	128.2

In this scenario, it was found that the TET increased to 151.7 seconds compared with 81.8 seconds in scenario 3 (see Table 76). During their evacuation passengers from the far right aisles were forced to make their way to the L1 and L2 exits. This created considerable congestion in the rear cross aisle restricting the access of passengers in the forth from left aisle from gaining direct access to R2. As a result, this aisle was the last to empty out with passengers eventually switching to empty adjacent aisles (see Figure 139 at 113 and 123 seconds). Rather than representing each passenger, this figure displays the population density (passengers/m^2) as a shaded contour, the darker the colouring the higher the population density. As the L2 exit had a much larger supply of passengers than the previous examples, the flow rate achieved by this exit increased to approach its theoretical maximum (see Table 76). Congestion rapidly developed in the rear cross aisle as can be seen with the average CWT reaching 47.9 seconds, an increase of some 53% over that of Scenario 3.

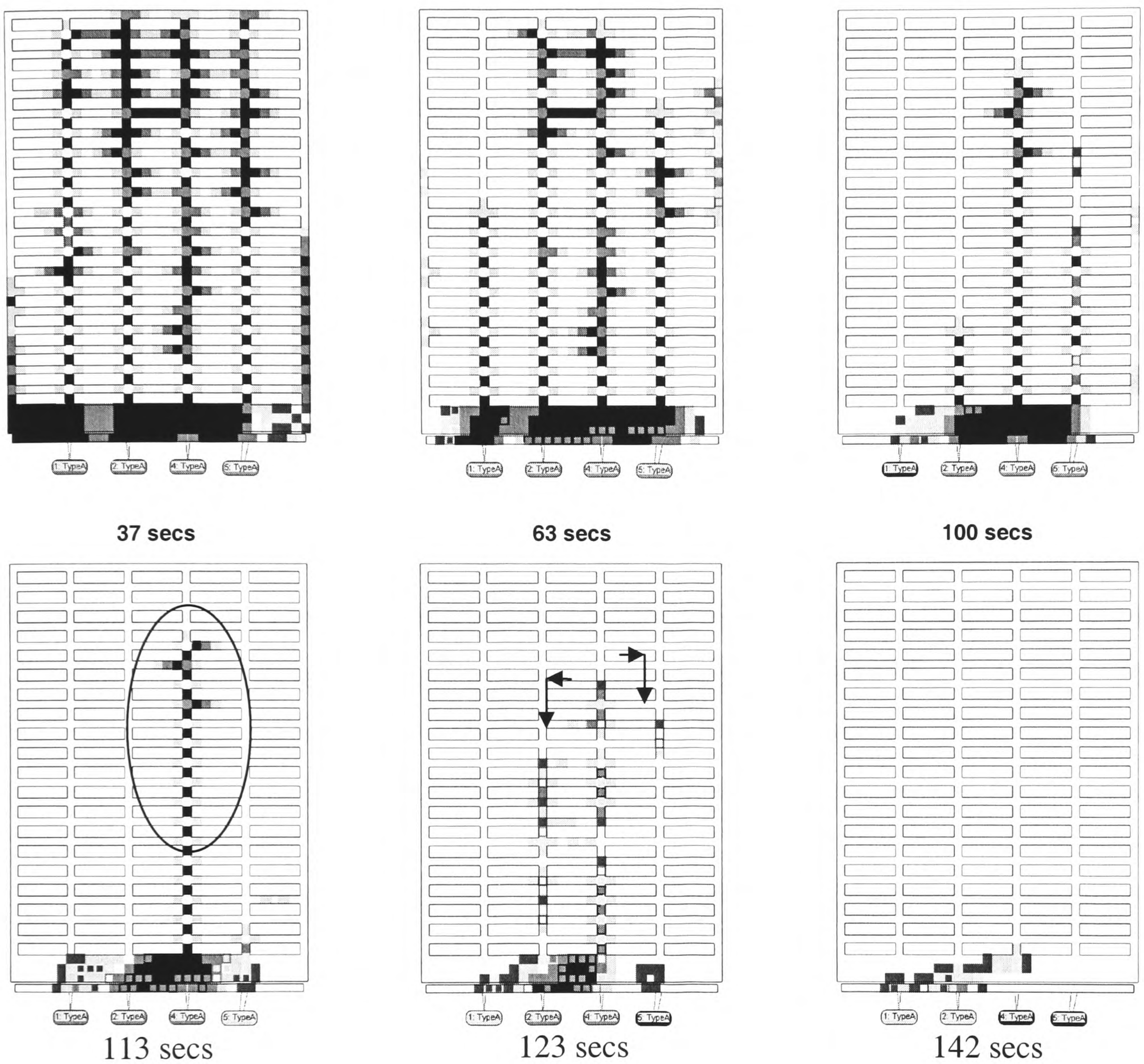


Figure 139: Population density diagrams showing congestion regions throughout aircraft at various times during scenario 4 – Passengers in the ringed area begin to aisle swap

Using the aisle swapping algorithms some passengers towards the end of the evacuation swapped from the slow moving aisles to the essentially empty adjacent aisles (see the ringed area in Figure 139). In these simulation passengers queued patiently for much of the simulation. However, towards the end of the simulation many passengers were exposed to conditions in which aisle swapping could take place and eventually a passenger decided to swap aisles. Once a passenger had swapped aisles numerous others decided to do the same. In this respect the qualitative pattern of aisle swapping in these simulations reflects the findings of 90-second certification trials (see Chapter 5). In this study the application of the aisle swapping algorithms not only generated a faster evacuation of the aircraft as a whole but also allowed a more realistic representation of passenger movement within this type of aircraft cabin.

The effect of the passenger redirection model was that passengers in the vestibule area would redirect to adjacent exits. In doing so they would not simply determine before –hand that they would ignore the nearest exit. What transpired within the model was that passengers from the periphery of the exit queue would sometimes redirect to the adjacent exit (see Figure 140 (c)). An interesting result of these simulation as that some passengers that were initially located on the opposite side of the exit vestibule to the alternative exit (see Figure 140 (a) would end up redirecting themselves towards an exit that was further away (see Figure 140 (c)). In doing so they would not decide to redirect themselves past the nearest exit before reaching it (i.e. at Figure 140 (a)), but would join the queue and then get jostled from one side to the other (see Figure 140 (b), at which point they may and then decide to redirect (see Figure 140(c)). In these simulations the passenger redirection model generated more realistic passenger behaviour in this aircraft configuration and also decreased the evacuation time for the aircraft as a whole.

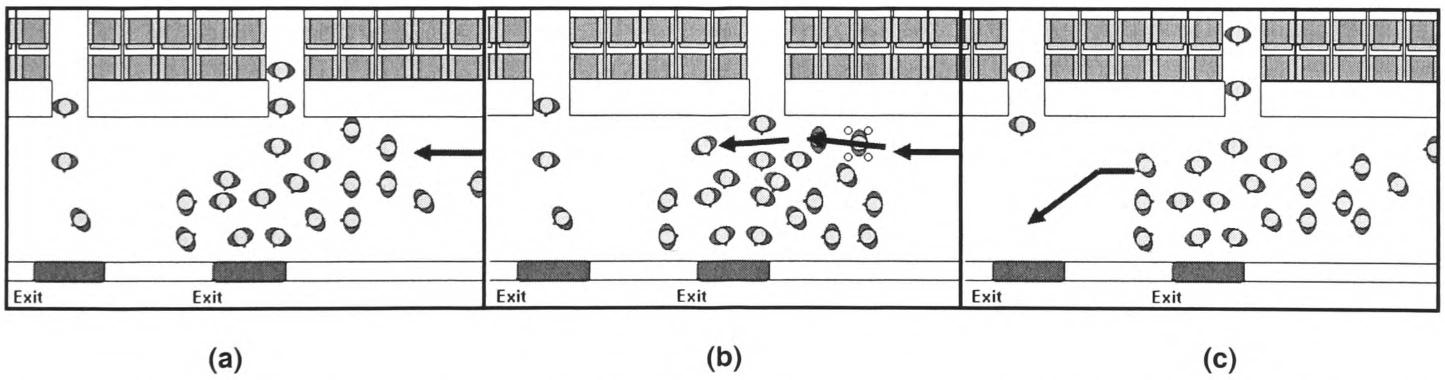


Figure 140: Examples of redirection behaviour, (a) shows a passenger joining the queue and (b) shows them being jostled from one side of the queue to another, and (c) shows a show a passenger redirecting from the periphery of the exit queue

A finding of this scenario was that the depth of the rear cross aisle was of paramount importance to the evacuation of this type of aircraft. With a deeper cross-aisle allowing the merging flows of passengers more room to manoeuvre. Another interesting feature of this simulation was the uneven distribution of passengers between the two available exits. In this case on average some 57% of the passengers used the L2 exit, the nearest exit to the majority of passengers. In addition, given the imbalance in exit usage it may be necessary to employ cabin crew to redirect passengers to their most optimal exits.

This study has demonstrated how evacuation modelling can be used to assess the evacuation efficiency and appropriateness of BWB certification requirements. Indeed this study raised questions regarding the applicability of the current 90-second certification methodology for this type of aircraft.

8.4 The application of evacuation modelling to accident investigation: Manchester, 1985

The final demonstration case examines a previous aircraft accident and how a more rigorous certification methodology possibly involving evacuation modelling technology could have revealed the potential for the aircraft disaster to occur. This study is yet to be published and so will be described in full.

On the 22nd of August 1985, a B737-300 suffered an uncontained engine failure and fire during its take-off roll at Manchester Airport, England [10]. The captain aborted take-off and stopped the aircraft at the side of the runway where evacuation ensued. The prevailing wind caused a fire plume from the left engine to be directed onto the aircraft fuselage (see Figure 141). The fire penetrated the cabin initially through the aft right exit. During the evacuation, two of the four cabin crewmembers and 53 of the 131 passengers onboard the aircraft died from the effects of the fire and toxic gases and a further 15 passengers were injured.

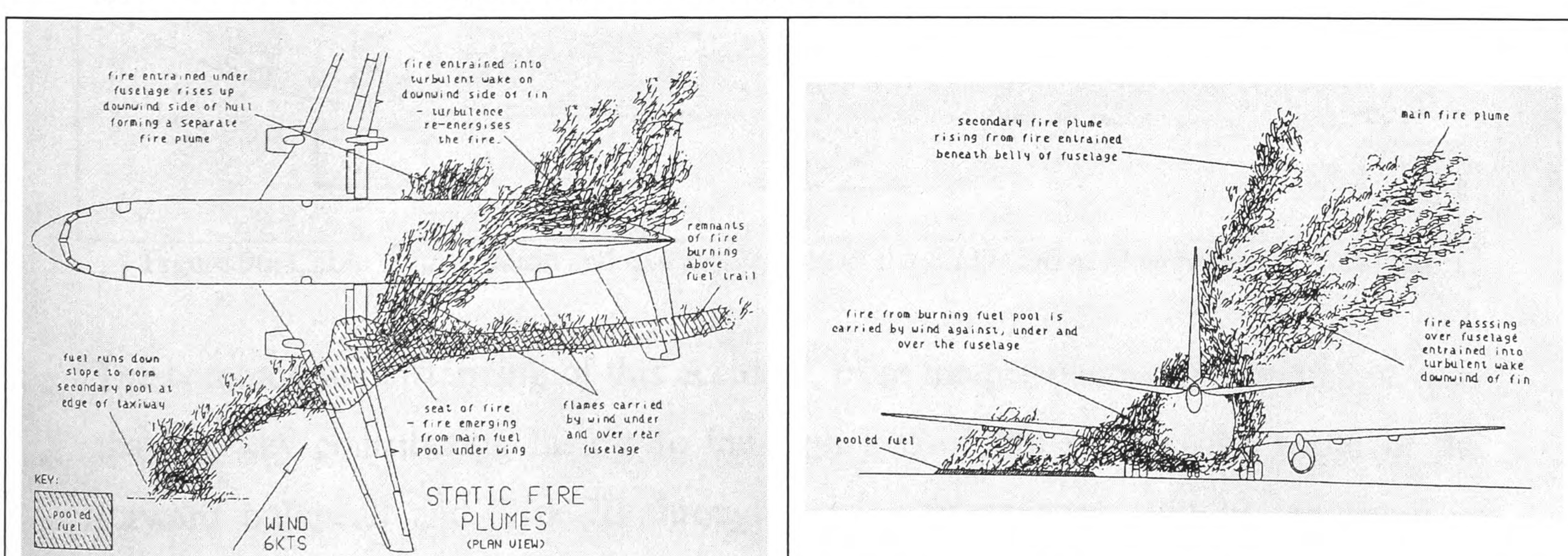


Figure 141: Static fire plumes during the Manchester accident in 1985 [10]

The number of deaths resulted from a combination of the extremely hostile conditions within the cabin and the protracted time required to evacuate the aircraft. During the incident fire, toxic gas and smoke penetrated the cabin via a combination of the slightly open AR exit and burn-through the cabin windows/walls. Numerous passengers stated that they had difficulty breathing. Some described holding their breath and smoke obscuring their vision. Possibly the most graphic survivor account from this accident is from a 50 year old male seated in 8D. This passenger described the build up of smoke particulate within the cabin during his evacuation causing such a problem that he used his handkerchief to wipe soot away from his eyes so that he could see better. In addition, cabin crew stated that the smoke forced them down onto their hands and knees during the evacuation.

In total there were three exit pairs fitted to this aircraft. From front to rear they were of, Type-I, Type-III and Type-I. Of these only the forward left (FL), forward right (FR) and right overwing (ROW) exits were utilised. During the evacuation passengers and crew described difficulties in opening most of the exits. Indeed the ROW exit was opened by a passenger after approximately 45 seconds and the FL and FR by a crewmember after approximately 15 seconds and 120 seconds. The aft right exit was initially opened however it partially closed due to fire and smoke. The aft left and left overwing exits were not opened due to fire and smoke outside of the aircraft.

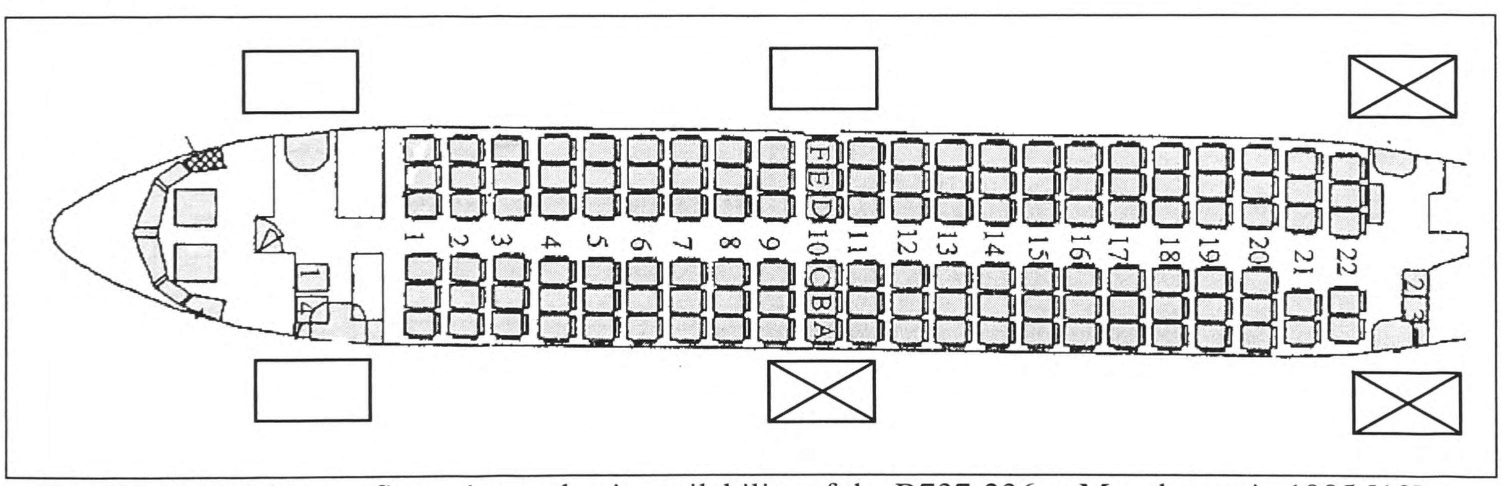


Figure 96: Cabin configuration and exit availability of the B737-236 at Manchester in 1985 [10]

The common understanding of this accident, from the perspective of evacuation, was that the key contributing factors to the high loss of life were a) the width of the forward bulkhead and Type-III through seating passageway and b) the delay in opening some of the exits. In this chapter the airEXODUS evacuation model is used to simulate a similar accident scenario. The fire data used in the simulation is derived from full-scale fire tests undertaken by the FAA technical centre in Altantic City using a C133 test facility. The airEXODUS evacuation model is used to explore a Manchester 'type' fire scenario so as to evaluate the impact on the evacuation of the exit opening delays.

In addition an evaluation of the evacuation performance of this aircraft under 'typical' 90-second conditions is considered. As part of this assessment a more rigorous set of 90-second certification scenarios are explored to demonstrate how evacuation modelling can be used to explore more relevant accident conditions as part of the certification process.

8.4.1 Method

8.4.1.1 The airEXODUS cabin configuration

Exact data concerning the dimensions of the cabin configuration of the B737-236 that was involved in the Manchester accident was not available within the air accident report [10]. As part of this analysis a B737-300 was constructed. Since the width, length and exit positions in the B737-236 are identical to that of the B737-300, it was possible to generate an approximation of the Manchester configuration that matched the overall dimensions of the Manchester aircraft and exit positions (see Figure 142). In the airEXODUS model the actual seat pitches may vary from that of Manchester by one or two inches, however these differences are not thought to have an impact upon the analysis undertaken in this work. Finally, within the model the forward bulkhead aperture is wide enough to accommodate one passenger at a time.

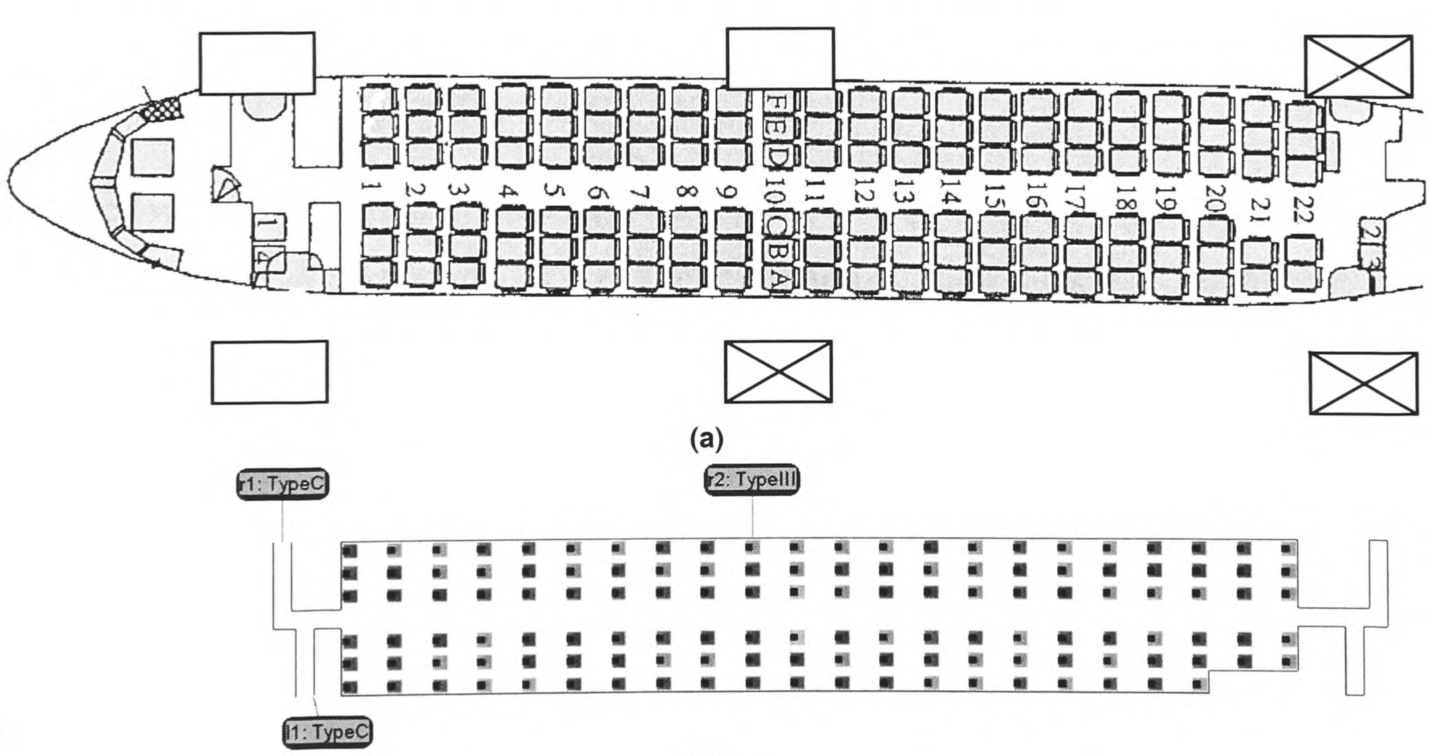


Figure 142: (a) The cabin configuration and exit availability of the B737-236 at Manchester in 1985 [10] and (b)the airEXODUS model

8.4.1.2 Exit availability

To examine the impact of exit availability two exit configurations will be considered in this paper. The first is similar to that witnessed in the Manchester disaster in 1985 [10]. Available exits are therefore the FR and FL Type-I exits and the ROW Type-III exit.

The second exit availability configuration is akin to a 90-second certification trial in which all of the exits down one side of the aircraft are available. In this configuration available exits are the FR Type-I, ROW and AR Type-I exits.

A feature of the Manchester accident was that the crew and passengers experienced significant difficulty in opening the three exits (FR, FL, ROW). The cabin crewmember located at the front of the aircraft tried to open the FR exit, however during its activation *"the slide container lid jammed on the doorframe preventing further movement of the door"* [10]. He tried to free the mechanism for a few seconds before abandoning it and moving to and opening the FL exit. The FL exit is thought to have been opened approximately 25 seconds after the call to evacuate. The cabin crewmember then returned to the FR exit and continued trying to open it. He eventually managed to open the exit and deploy the slide however the exit was not fully ready for use until some 1 minute 10 seconds after the call to evacuate.

The over-wing Type-III exit was opened by a passenger approximately 45 seconds after the evacuation had begun. To examine the impact that these exit opening delays had on the overall evacuations scenarios will be modelled both with and without exit opening delays.

8.4.1.3 Population specification

The population specification has been determined using the standard mix as specified for 90-second certification trials [12]. In total 129 of the 131 seats were occupied during the flight. Thus within the airEXODUS model a population of 129 has been generated.

8.4.1.4 Fire data from an FAA C133 Technical Assessment Centre in Atlantic city

In the early nineties the FAA conducted a series of fire tests to determine the benefit of water spray systems using their standard 'C133' methodology [170]. One of these tests [172] involved the use of the fuselage of fully fire hardened B707 to a kerosene fuel pan fire entering through a single exit aperture with 15 fire blocked seats and 4 stowage bins located adjacent to the exit aperture (see Figure 143). The base-case data from this experiment provides data that is used in this paper.

The fire test configuration was similar to that of previous FAA 'C133' fire tests involving a single open exit and consequently poor ventilation and an inevitable flash-over at approximately 90 seconds. By contrast in the Manchester accident a pressure gradient developed within the cabin that pulled fire and smoke into the cabin through the aft exits and at the same time ventilated some of the fumes via the forward exits. Unlike the FAA test, increased ventilation led to some small flash-fires but prevented flash-over occurring [10].

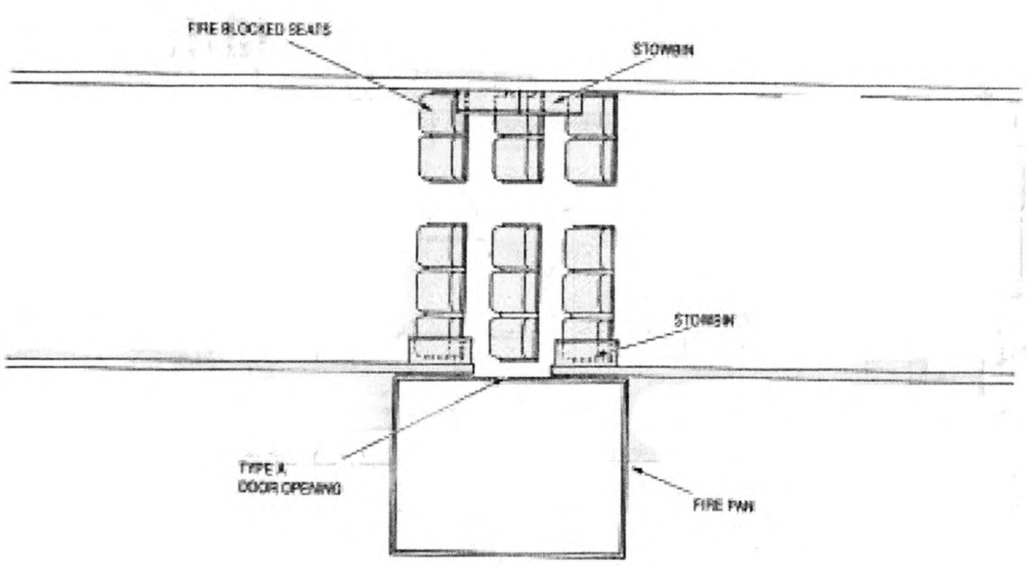


Figure 143: Experimental configuration [172]

It is therefore apparent that very different ventilation affects and therefore fire dynamics would have been present in the Manchester air disaster than in results generated using the typical FAA 'C133' test methodology. Whilst not ideal the FAA data does at least provide fire data from a real fire test and will be used in these scenarios.

8.4.1.5 Cabin description and measurement stations

The length of the experimental cabin was approximately 29 metres. Within the cabin six thermocouple trees were spaced evenly throughout at stations 400, 590, 780, 970, 1160 and 1380 inches from the forward bulkhead. Each tree consisted of 7 thermocouples vertically spaced one foot apart. Four calorimeters were fitted at station 590, 780, 1160 and 1380 inches from the forward bulkhead and were 3 foot 6 inches from the floor. Three of the calorimeters pointed longitudinally through the fuselage towards the door (590, 780 and 1380) whilst the calorimeter at 1160 pointed lateral to the fuselage and directly at the exit. Two smoke detector trees were installed; at 400 and 780 inches from the forward bulkhead. Each smoke detector tree consisted of detectors at 1 foot and 6 inches, 3 foot 6 inches, and 5 foot and six inches from the floor. Two gas analysis (CO, CO_2 and O) stations were installed on the smoke detector trees at 3 foot 6 inches and 5 foot 6 inches from the floor (see Figure 144).

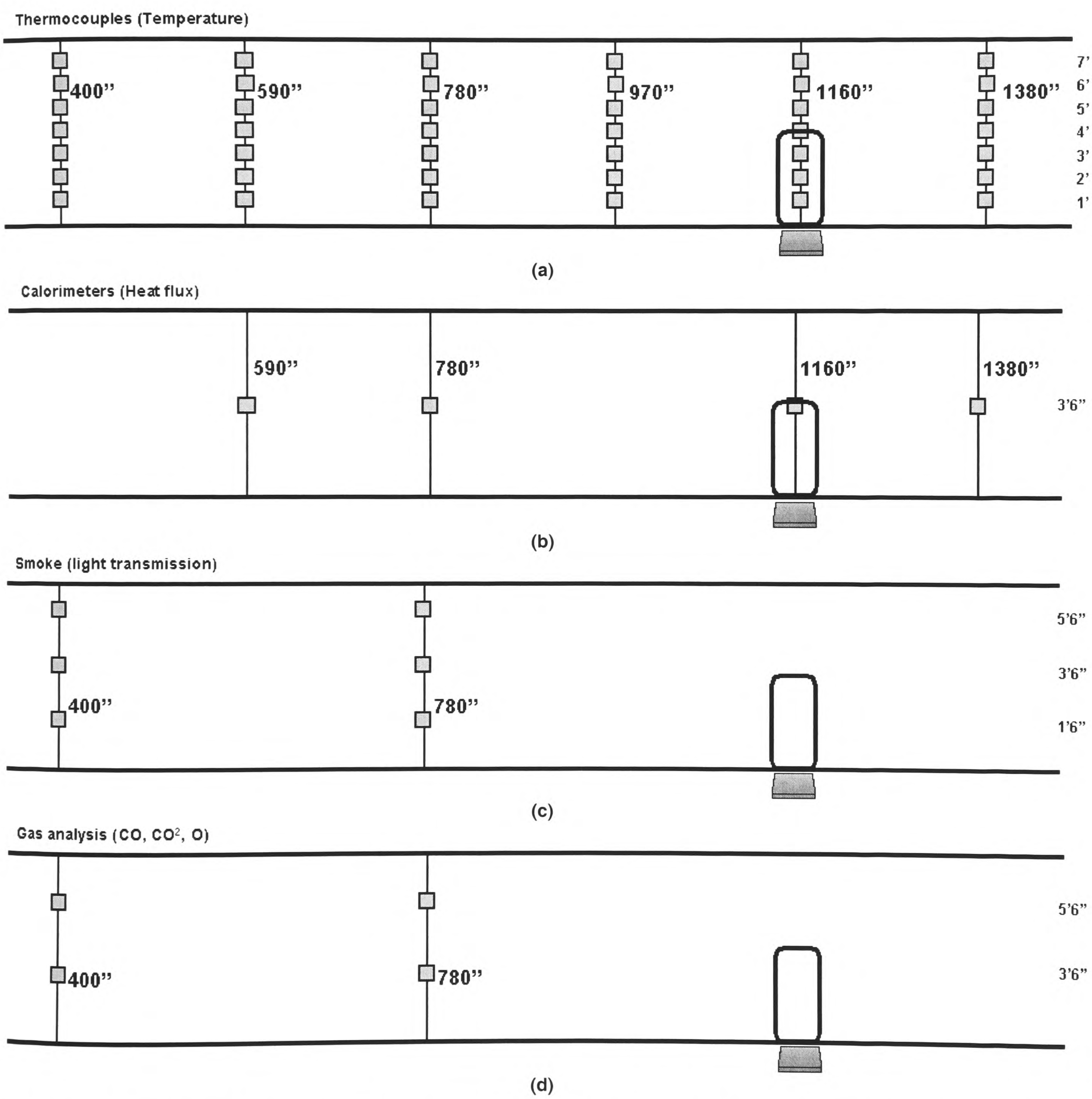


Figure 144: Experimental measurement apparatus; (a) thermocouples, (b) calorimeters, (c) smoke meters and (d) gas analysis

8.4.1.6 Converting the fire data into airEXODUS hazards

Within airEXODUS it is possible to specify fire hazard data for each node within the model, i.e. each $0.5m^2$ region of floor space. However, the fire test procedure recorded data at only a handful of locations inside the aircraft cabin. Thus, data had to be converted (in a realistic manner) to provide the type of hazard data that could be used within the model.

8.4.1.7 Fitting the fire data to the aircraft geometry

Actually fitting the volume of the fire hazard to that of the cabin proved difficult. Whilst, the width of the B737-236 cabin (the EXODUS model) was the same as that of the B707 fire test configuration, the B737-236 cabin was approximately 22 metres in length compared to the 29 metres of the test cabin. The length from the test cabin door through which the fire emanates to the forward bulkhead was 21 metres. This is similar to the total length of the B737-236. Fire data from test facility as measured from the front bulkhead down to the aft door (21m) was used to represent the fire concentration within the airEXODUS model of the B737 (see Figure 145). Data 8m aft of the test facility aft door was not used within the airEXODUS model.

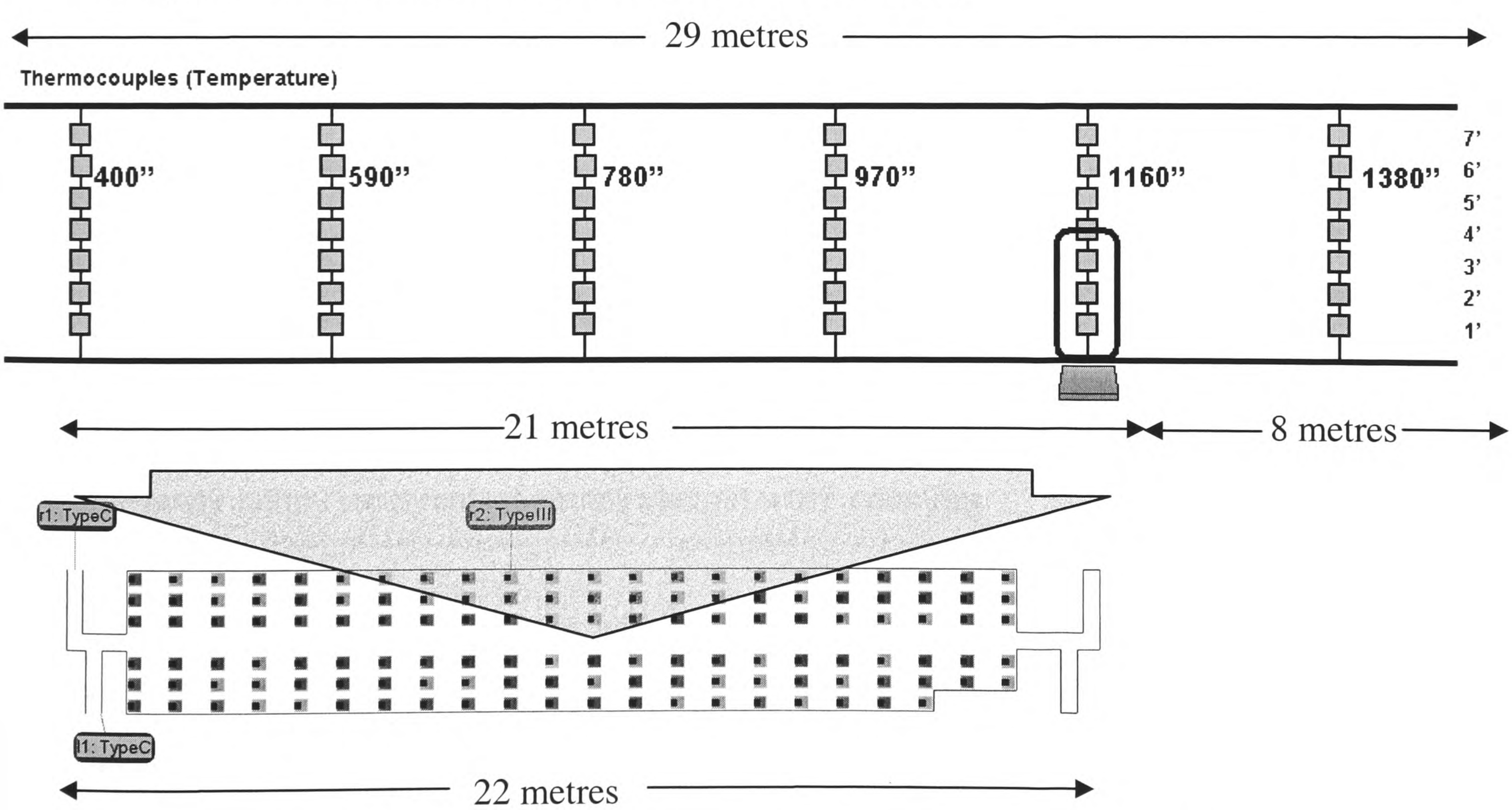


Figure 145: The dimensions of (a) the cabin used in the B707 fire test and (b) the B737-236 airEXODUS geometry

Whilst not ideal, fitting the volume of the experimental fire in this manner ensures that the aft exit is correctly positioned relative to the total cabin length. However, it is also apparent that some of the total hazard, which may have been reflected forwards by the aft bulkhead, has been ignored. Furthermore, bulkheads and monument positioned within the B737 airEXODUS model do not reflect those of the test configuration. A consequence of this approach is that conditions within the airEXODUS B737 are less severe than would be expected had the test facility been a faithful reproduction of the airEXODUS B737.

8.4.1.8 Converting the fire data to airEXODUS hazards

Within airEXODUS upper and lower hazard layer can be defined for each node in the model whereas the fire data generated only a handful of measurements from the test cabin. Having determined the area of the fire hazard that would be used within the model the next step was to determine how the fire data could be converted to an appropriate form for use in airEXODUS.

The first stage of this process was to decide upon which measurements would represent upper and lower temperatures/gas values within the model. From the fire data, thermocouple data was available at 1-7 feet vertical heights whilst calorimeter data was only available at height of 3ft 6 inches from the floor. Gas concentrations were measured at 3ft 6 inches and 5ft 6 inches from the cabin floor and smoke was measured at 1ft 6inches, 3ft 6inches and 5ft 6inches.

It was determined that the upper layer height be fixed at 5ft 6 inches and the lower layer at 3ft 6 inches from the floor. These heights were primarily influenced by the availability of data from the fire test. However, importantly at these heights the upper layer was representative of head height for an average sized erect passenger and that the lower height represents their head height when crawling.

Gas concentrations at each layer within the model correspond directly to the heights of the measurement equipment used in the experiments, i.e. 3ft 6 inches and 5ft 6 inches. Since calorimeter data was only available at 3ft 6 inches, the upper layer values were set to that of the lower layer (the calorimeter 3ft 6 inches from the floor). Finally, since temperature was measured with a vertical spacing of 1 foot, it was necessary to use the average value between 3-4 feet and 5-6 feet to set the temperature at 3ft 6 inches and 5ft 6 inches.

The second stage of converting the fire data involved designing the finest hazard zone mesh using the measurement stations from the experimental data. Within the model the fire hazard was divided into five distinct zones based on the spacing of the experimental apparatus (400", 590", 780", 970" and 1160"). Five zones represented the finest possible hazard mesh given the limited number of measurement stations within the experiment. Each zone encompassed the total width of the aircraft and was 4.8 metres (9ft) long. Within the model all of the nodes within a particular zone will be assigned the same hazard data. This assumes that the hazards are uniform over the volume of the zone. The hazard zone configuration used within the model can be seen in Figure 146.

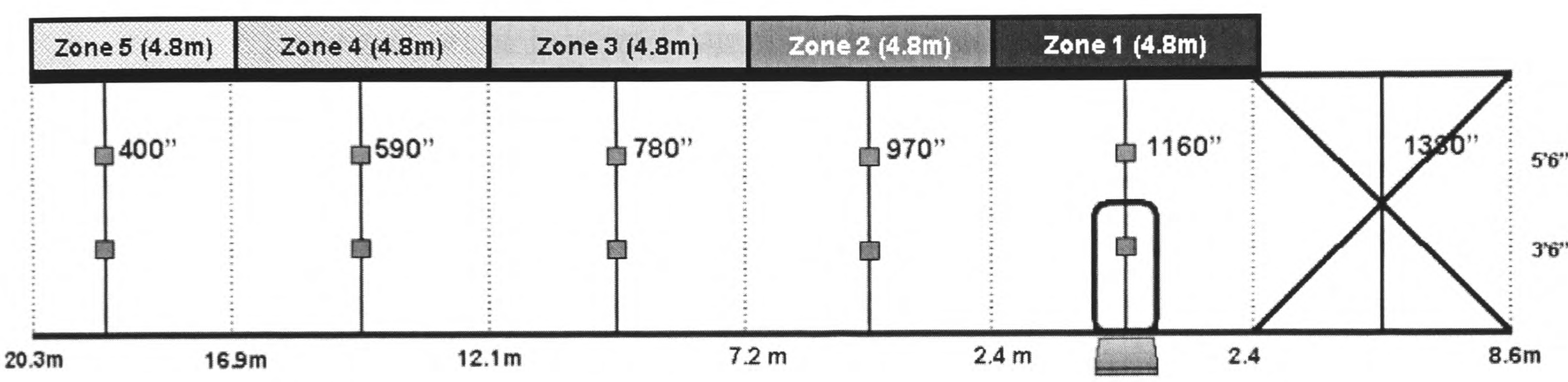


Figure 146: Zoned representation of the experimental fire hazard used within airEXODUS

Finally, whilst unique thermocouple data was available for every zone, unique data was not provided by the fire test experiment for some fire parameters at some zones (see Table 77). Thus, it was necessary to approximate hazard data in some zones using values from adjacent zones and where possible averages from surrounding zones (see Table 77).

Table 77: Summary of available data and that which was used in the model

Summary of the experimental measurement stations at each zone					
Measurement	**Zone 5 400"**	**Zone 4 590"**	**Zone 3 780"**	**Zone 2 970"**	**Zone 1 1160"**
Thermocouple	Present	Present	Present	Present	Present
Smoke	Present	Not present	Present	Not present	Not present
Gas	Present	Not present	Present	Not present	Not present
Calorimeter	Not present	Present	Present	Not present	Present
Summary of the data used within the airEXODUS model					
Measurement	**Zone 5 400"**	**Zone 4 590"**	**Zone 3 780"**	**Zone 2 970"**	**Zone 1 1160"**
Thermocouple	Unique	Unique	Unique	Unique	Unique
Smoke	Unique	Use mean 400+780	Unique	Use 780	Use 780
Gas	Unique	Use mean 400+780	Unique	Use 780	Use 780
Calorimeter	Use 590	Unique	Unique	Use 780	Unique

Table 78: Description of fire hazard used in each zone - Lower layer values in brackets

Time (seconds)	HEAT (Degress C)					Heat (KW/m2)				
	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1
0-30	19 (19)	19 (19)	19 (19)	19 (19)	19 (19)	N/A	0 (0)	0 (0)	N/A	0 (0)
30-40	19 (19)	19 (19)	19 (19)	19 (19)	57 (54)	N/A	0 (0)	0 (0)	N/A	51 (51)
40-50	19 (19)	19 (19)	20 (19)	20 (19)	86 (74)	N/A	0 (0)	0 (0)	N/A	58 (58)
50-60	19 (19)	19 (19)	20 (19)	21 (20)	114 (94)	N/A	0 (0)	1 (1)	N/A	66 (66)
60-70	19 (19)	19 (19)	21 (19)	23 (20)	142 (114)	N/A	0 (0)	1 (1)	N/A	73 (73)
70-80	28 (19)	29 (21)	39 (21)	41 (24)	246 (176)	N/A	0 (0)	4 (4)	N/A	103 (103)
80-90	36 (20)	38 (22)	56 (23)	58 (28)	350 (238)	N/A	0 (0)	6 (6)	N/A	132 (132)
90-100	45 (20)	48 (24)	74 (25)	76 (32)	454 (300)	N/A	0 (0)	8 (8)	N/A	161 (161)
100-110	87 (41)	88 (42)	123 (41)	169 (51)	607 (503)	N/A	2 (2)	8 (8)	N/A	166 (166)
110-120	130 (63)	129 (60)	173 (58)	263 (69)	760 (707)	N/A	4 (4)	8 (8)	N/A	170 (170)
120-130	172 (84)	169 (78)	222 (74)	356 (88)	913 (910)	N/A	6 (6)	8 (8)	N/A	174 (174)
130-150	238 (150)	267 (147)	334 (152)	549 (168)	1054 (886)	N/A	7 (7)	10 (10)	N/A	167 (167)
150-160	271 (183)	316 (181)	391 (191)	646 (207)	1124 (874)	N/A	8 (8)	14 (14)	N/A	151 (151)
160-170	269 (189)	316 (188)	368 (204)	545 (262)	888 (720)	N/A	8 (8)	13 (13)	N/A	111 (111)
170-180	267 (194)	311 (194)	345 (216)	445 (318)	652 (567)	N/A	8 (8)	12 (12)	N/A	70 (70)
180-210	264 (199)	302 (201)	323 (229)	345 (373)	416 (413)	N/A	7 (7)	11 (11)	N/A	30 (30)
210-240	193 (163)	209 (160)	214 (184)	201 (151)	257 (217)	N/A	6 (6)	7 (7)	N/A	10 (10)
240-270	135 (119)	164 (135)	166 (143)	129 (124)	173 (146)	N/A	3 (3)	4 (4)	N/A	7 (7)
270-300	103 (98)	126 (103)	127 (102)	76 (76)	121 (93)	N/A	2 (2)	2 (2)	N/A	3 (3)

Time (seconds)	Carbon Monoxide (parts per million)					Carbon Dioxide (%)				
	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1
0-30	0 (0)	N/A	0 (0)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
30-40	0 (0)	N/A	0 (0)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
40-50	0 (0)	N/A	0 (0)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
50-60	0 (0)	N/A	0 (0)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
60-70	0 (0)	N/A	0 (0)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
70-80	1167 (0)	N/A	1220 (0)	N/A	N/A	0 (0)	N/A	1 (0)	N/A	N/A
80-90	2333 (0)	N/A	2440 (0)	N/A	N/A	0 (0)	N/A	2 (0)	N/A	N/A
90-100	3500 (0)	N/A	3660 (0)	N/A	N/A	1 (0)	N/A	2 (0)	N/A	N/A
100-110	5100 (1233)	N/A	5573 (67)	N/A	N/A	2 (1)	N/A	3 (0)	N/A	N/A
110-120	6700 (2467)	N/A	7487 (133)	N/A	N/A	3 (1)	N/A	4 (0)	N/A	N/A
120-130	8300 (3700)	N/A	9400 (200)	N/A	N/A	4 (2)	N/A	5 (0)	N/A	N/A
130-150	10000 (5550)	N/A	10433 (200)	N/A	N/A	5 (3)	N/A	6 (0)	N/A	N/A
150-160	13400 (9250)	N/A	12500 (200)	N/A	N/A	7 (6)	N/A	8 (0)	N/A	N/A
160-170	16700 (10975)	N/A	16250 (250)	N/A	N/A	7 (9)	N/A	10 (0)	N/A	N/A
170-180	20000 (12700)	N/A	20000 (300)	N/A	N/A	8 (10)	N/A	10 (0)	N/A	N/A
180-210	20000 (15400)	N/A	20000 (300)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
210-240	13500 (11500)	N/A	19000 (300)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
240-270	8600 (7950)	N/A	10300 (200)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
270-300	6900 (5330)	N/A	6850 (100)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A

Time (seconds)	Oxygen (%)					Smoke (Extinction Coefficient)				
	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1	Zone 5	Zone 4	Zone 3	Zone 2	Zone 1
0-30	21 (21)	N/A	21 (21)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
30-40	21 (21)	N/A	21 (21)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
40-50	21 (21)	N/A	21 (21)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
50-60	21 (21)	N/A	21 (21)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
60-70	21 (21)	N/A	21 (21)	N/A	N/A	0 (0)	N/A	0 (0)	N/A	N/A
70-80	20 (21)	N/A	20 (21)	N/A	N/A	2 (0)	N/A	2 (0)	N/A	N/A
80-90	20 (21)	N/A	19 (21)	N/A	N/A	12 (0)	N/A	6 (0)	N/A	N/A
90-100	19 (21)	N/A	18 (21)	N/A	N/A	15 (12)	N/A	15 (0)	N/A	N/A
100-110	18 (20)	N/A	17 (19)	N/A	N/A	15 (12)	N/A	15 (0)	N/A	N/A
110-120	17 (19)	N/A	15 (17)	N/A	N/A	15 (12)	N/A	15 (0)	N/A	N/A
120-130	15 (17)	N/A	14 (14)	N/A	N/A	15 (12)	N/A	15 (5)	N/A	N/A
130-150	12 (14)	N/A	12 (13)	N/A	N/A	15 (11)	N/A	15 (7)	N/A	N/A
150-160	10 (12)	N/A	10 (11)	N/A	N/A	15 (10)	N/A	15 (12)	N/A	N/A
160-170	9 (10)	N/A	8 (9)	N/A	N/A	15 (10)	N/A	15 (13)	N/A	N/A
170-180	7 (8)	N/A	7 (7)	N/A	N/A	15 (10)	N/A	15 (13)	N/A	N/A
180-210	6 (7)	N/A	6 (6)	N/A	N/A	15 (10)	N/A	15 (14)	N/A	N/A
210-240	7 (7)	N/A	7 (9)	N/A	N/A	15 (10)	N/A	12 (15)	N/A	N/A
240-270	8 (7)	N/A	11 (13)	N/A	N/A	12 (10)	N/A	12 (15)	N/A	N/A
270-300	8 (8)	N/A	10 (8)	N/A	N/A	9 (8)	N/A	12 (15)	N/A	N/A

8.4.1.9 Summary of the fire definition used within the model

The final fire scenario that will be used in airEXODUS comprises of five zones each with upper and lower layer values. Each zone encompasses the total width of the aircraft and is 4.8 metres (9ft) long.

The evolution of the fire scenario can be seen in Table 78 and is briefly described. It can be seen that for the first 90 seconds conditions within the cabin, whilst hostile are generally survivable in areas not adjacent to the fire. Approximately 80 seconds into the evacuation conditions beging to become less tenable with radiative flux increasing throughout the cabin. This is coupled with increases in temperature, a drop in oxygen and increases in CO and CO_2. From approximately 80 seconds onwards conditions within the aircraft are extremely hostile and survival is extremely unlikely.

8.4.1.10 Limitations with the fire data

It is recognised that the fire used in this study is not fully representative of the fire present in the Manchester accident. The fire data used in this study involves a flash-over after approximately 90 seconds, in contrast a traditional flashover did not occur in the Manchester accident, as the report states,

"Contrary to conventional wisdom, a full flashover in the cabin did not occur, although clearly a number of brief flash fires did occur as vapours in the ceiling space ignited."[10]

The majority of fire fatalities in the Manchester accident were due to inhalation of toxic gases that resulting from burning cabin furnishings and linings. In contrast the experimental fire contained only a small number of passenger seats. Whilst these caught fire they would not have produced similar levels of toxic gases to those that occur in Manchester 1985. Furthermore, experimental apparatus was not provided for measuring toxic gases, such as Hydrogen Cyanide.

Furthermore, it is recognised that in the Manchester accident the AR, ROW, FR and FL exits were open during the fire incident whereas in the FAA fire test only the AL was open. This would lead to very different ventilation and circulation within the cabin, thus leading to different burning conditions.

Whilst these issues limit the comparisons that can be drawn between the simulations performed in this study and the Manchester evacuation itself this investigation demonstrates the potential use of evacuation modelling for examining fire scenarios. The modelled scenario also provides some new insight into the Manchester accident.

8.4.1.11 The scenarios

Two sets of scenarios are investigated in this study. The first set – the Scenario 1 series - comprises of two cases that make use of the fire data presented in the previous section and simulate the evacuation under emergency evacuation conditions. The scenario 1 series comprises the following two cases,

Scenario 1(a): A full-fire scenario with the Manchester available exits and with exit opening delays and crew bypass at the Type-III exit,

Scenario 1(b): A full-fire scenario with the Manchester available exits but without exit opening delays.

The first case is intended to simulate a Manchester type scenario as closely as possible and the second explores the possible outcome had the exits been opened more quickly.

Scenario 2 comprises four 90-second cases that demonstrate the evacuation of this aircraft under 90-second certification conditions. The purpose of these scenarios is to demonstrate what could have been learnt from a standard 90-second certification trial of this aircraft configuration using computer simulation and furthermore what could have been learnt had a more rigorous certification analysis been undertaken.

The first of the 90-second scenarios simulates a 'typical' 90-second certification trial for the aircraft. The model is first configured with one active exit from each exit pair as is the normal configuration for 90-second certification trials.

Scenario 2: A 'typical' 90-second certification trial.

This case is followed by three sub-cases. The first two maintain the rules of 90-second certification trial conditions but use a different combination of available exits,

Scenario 2(a): A 90-second scenario with the Manchester available exits but without exit opening delays,

Scenario 2(b): A 90-second scenario with the Manchester available exits but without exit opening delays and with crew bypass at the Type-III exit.

The final case subjects the aircraft to a more rigorous test in which the actual delays in opening the exits that occurred during the Manchester accident are used.

Scenario 2(c): A 90-second scenario with the Manchester available exits and with exit opening delays and crew bypass at the Type-III exit.

A summary of the scenarios and the model configuration can be seen in Table 79. All of the scenarios were simulated 1000 times in order to generate a range of results. The passengers were defined using standard tools within airEXODUS and represent a typical 90-second population. The 90-second population was randomly seated in the seats that were occupied during the Manchester accident.

Table 79: Summary of scenarios that are simulated

Scenario	Scenario type	Exit availability	Exit opening delays	Contains cabin crew procedures
1(a)	Fire simulation	FR, FL, ROW	70, 15, 45 seconds	Yes
1(b)	Fire simulation	FR, FL, ROW	All approximately 10 seconds	Yes
2	90-second conditions	FR, ROW, AR	All approximately 10 seconds	No
2(a)	90-second conditions	FR, FL, ROW	All approximately 10 seconds	No
2(b)	90-second conditions	FR, FL, ROW	All approximately 10 seconds	Yes
2(c)	90-second conditions	FR, FL, ROW	70, 15, 45 seconds	Yes

8.4.2 Results and discussion

8.4.3 The scenario 1 series: Evacuations involving fire

8.4.3.1 Passenger and crew behaviour

Within these scenarios passengers will make their own exit choice decisions based on visible congestion within the cabin. When doing so their visibility is limited by the level of smoke present within the cabin. During these scenarios smoke visibility algorithms within airEXODUS indicate that visibility is relatively good throughout the entire cabin for the first 50 seconds (see Figure 147 (a)). However, thereafter visibility deteriorates rapidly. Only 14 seconds later (at 64 seconds) visibility was reduced to just a few metres (see Figure 147(c)) and soon after visibility was all but obliterated (see Figure 147 (e)).

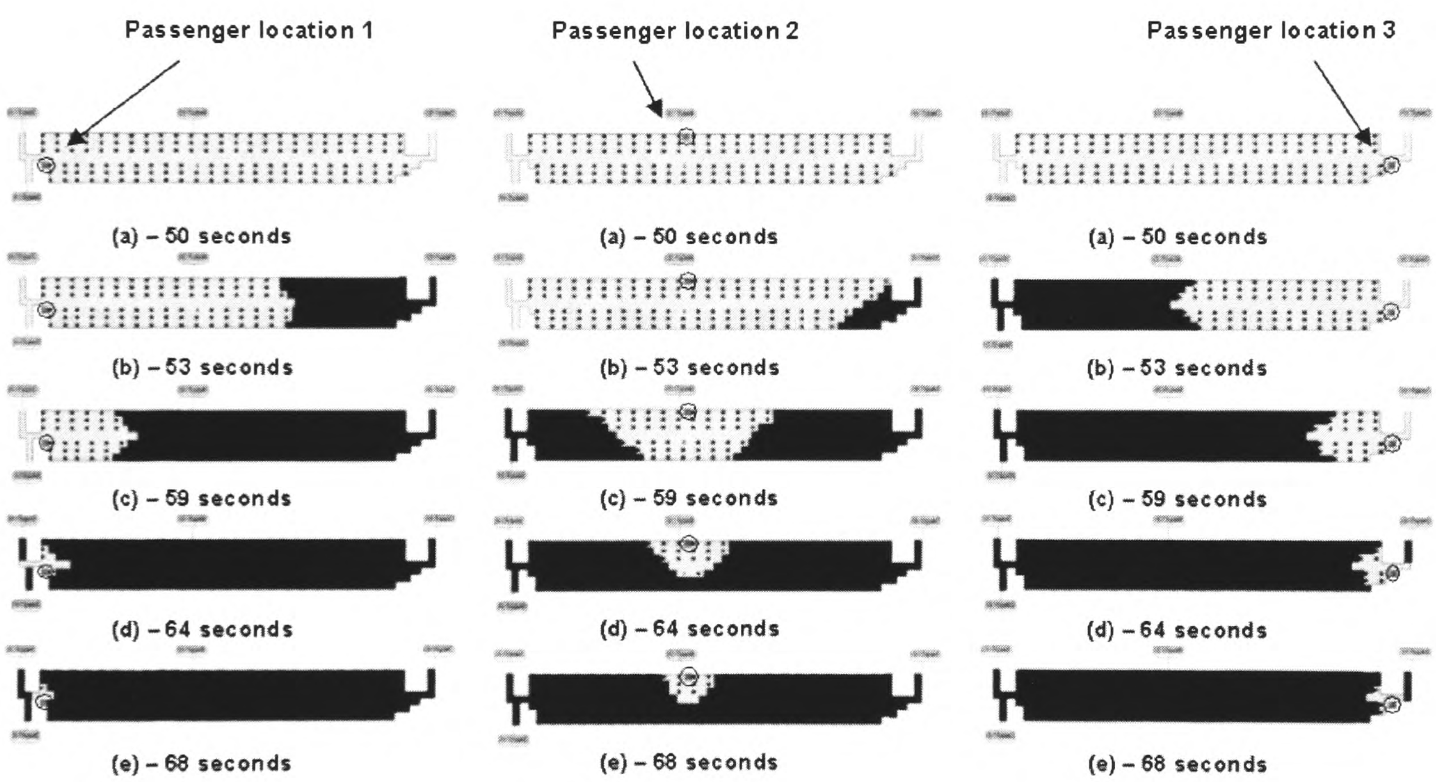


Figure 147: AirEXODUS smoke visibility calculations at head height at the forward and aft bulkheads and adjacent to the Type-III exit (black areas cannot be seen from the passenger locations)

In addition to making their own exit choice decisions within the Scenario 1 series simulations passengers will have the option of climbing over seating should they a) have the agility, b) have the will and c) become impatient from their natural path being obstructed by other passengers.

Finally, a cabin crew member has been located in the area opposite the active ROW exit and is responsible for redirecting passengers between the FR, FL and ROW exits. This crewmember will attempt to balance the number of evacuees that use each of the active exits. In doing the simulated crew will use information obtained from the environment via sight. The visual access of the crew will be limited according to the smoke conditions within the cabin (see Figure 147). Finally, when redirecting passengers the crew will have to convince them that their current exit choice is poor. Given the extreme levels of stress and anxiety that would be present during this type of evacuation in most instances the crew will be unable to achieve this and passengers will ignore the instructions of crew. This is a reflected in the model through the automatic adjustment of passenger motivation the details of which were outlined earlier.

8.4.3.2 Scenario 1(a): A full-fire scenario with the Manchester available exits and with exit opening delays and crew bypass at the Type-III exit

This scenario attempts to closely match the configuration found in the Manchester accident. In this scenario not only is the same exit availability used but also the same exit opening delays.

In scenario 1(a) on average 71 passengers evacuated in 114 seconds and 61 passengers died mainly from radiative heat. On average 6 passengers decided to climb seating with the average number of climbed seating being 2.7 seats. This compares reasonably well with the average number of seats that passengers stated they climbed (2.1 rows) during the Manchester accident. On average it took passengers 57.9 seconds to evacuate the aircraft with passengers spending on average 72% of their evacuation time stationary due to congestion.

In this scenario the model predicts an average of 61 passenger deaths whereas in the actual accident only 51 passenger deaths were recorded [10]. Recall that the fire used in this scenario was different to that which occurred during the real accident. In the Manchester accident passenger bodies were mainly found around the Type-III exit and in the aisle aft of the Type-III exit - the model predicts a similar distribution of seating locations for fatalities and pattern of corpses described as in the air accident report (see Figure 148).

To demonstrate the complexity of the passenger behaviour in this scenario we will consider in detail one of the 1000 repeat simulations (see Figure 149) in detail. During the first 25 seconds none of the exits are opened, as such passengers initially begin to queue for their nearest exits (overall movement pattern is denoted by the large arrows in Figure 149(a)). During this time seven passengers in the aft of the cabin perish from exposure to excessive levels of thermal radiation entering through the aft exit. In addition some passengers have already decided to climb over seating in order to improve their position (see collapsed seats in Figure 149(a)). After 25 seconds the L1 exit is opened and passengers begin to move forwards – again some passengers caught in seating begin to seat climb (see Figure 149(b)). Approximately 45 seconds into the evacuation the forward exit queue diminishes. Noticing this some of the passengers at the periphery of the ROW exit queue begin to redirect themselves to the forward exits (see Figure 149(b) and (c)). During this time the crew also see that the forward exit is short of passengers but generally are unable to redirect passengers to the forward exits, the passengers preferring to use their nearest exit. From 50-70 seconds thick smoke enters the cabin almost completely obliterating vision (see Figure 147). During this time some passengers at the periphery of the R2 exit queue can see the forward exits and choose to redirect however due to the varied smoke levels others do not. From approximately 50 seconds onwards passengers' agility and movement speeds are all negatively affected by the smoke. From this point only very fit young passengers have sufficient agility to continue to climb seats within the model (see Figure 149(d) and (e)). At 80-100 seconds conditions in the cabin become critical and the cabin flashes over – during this time numerous causalities occur. Two passengers in the forward section survive and on their hands and knees manage to crawl from the aircraft at 117 seconds (see Figure 149(f)).

To summarise, if this aircraft configuration is subjected to the FAA measured fire test conditions, and the exits availability is based on the Manchester configuration with exit opening delays, a disaster of equal magnitude to that which occurred in 1985 is predicted by the model.

Table 80: Summary of the results of Scenario 1(a)

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 1(a)	min	96.6	54.6	39.0	1.0	1.0	57.0	0.02
	mean	114.0	57.9	41.7	5.9	2.7	60.9	0.17
	max	123.1	63.3	45.7	11.0	4.4	66.0	0.31
	STDEV	5.0	1.9	1.2	2.1	0.7	1.9	0.08

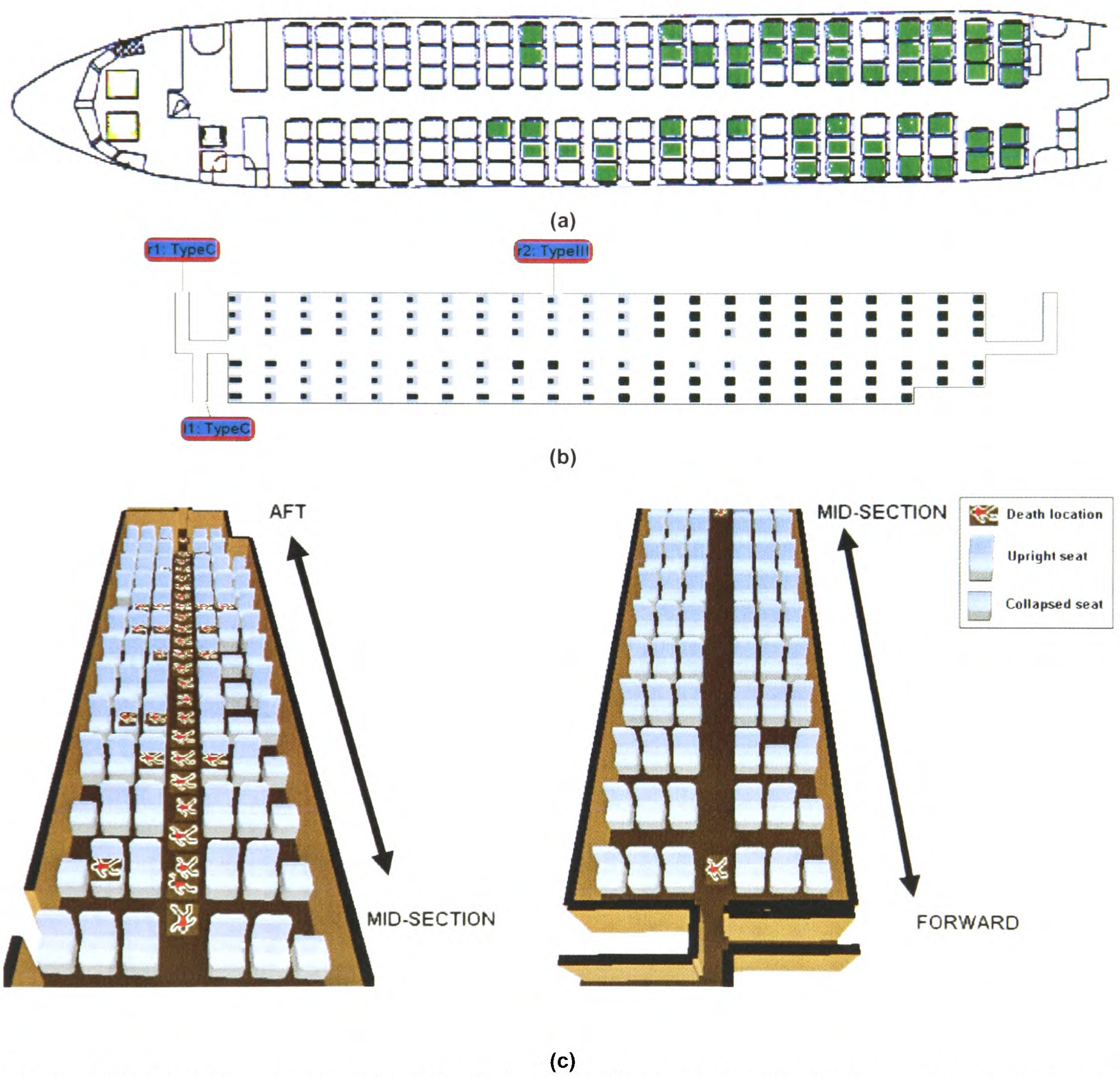


Figure 148: Original seating locations (shaded) of fatalities in (a) the Manchester accident in 1985, and (b) predicted by the model, and (c) a VR output from airEXODUS demonstrating the location of the corpses

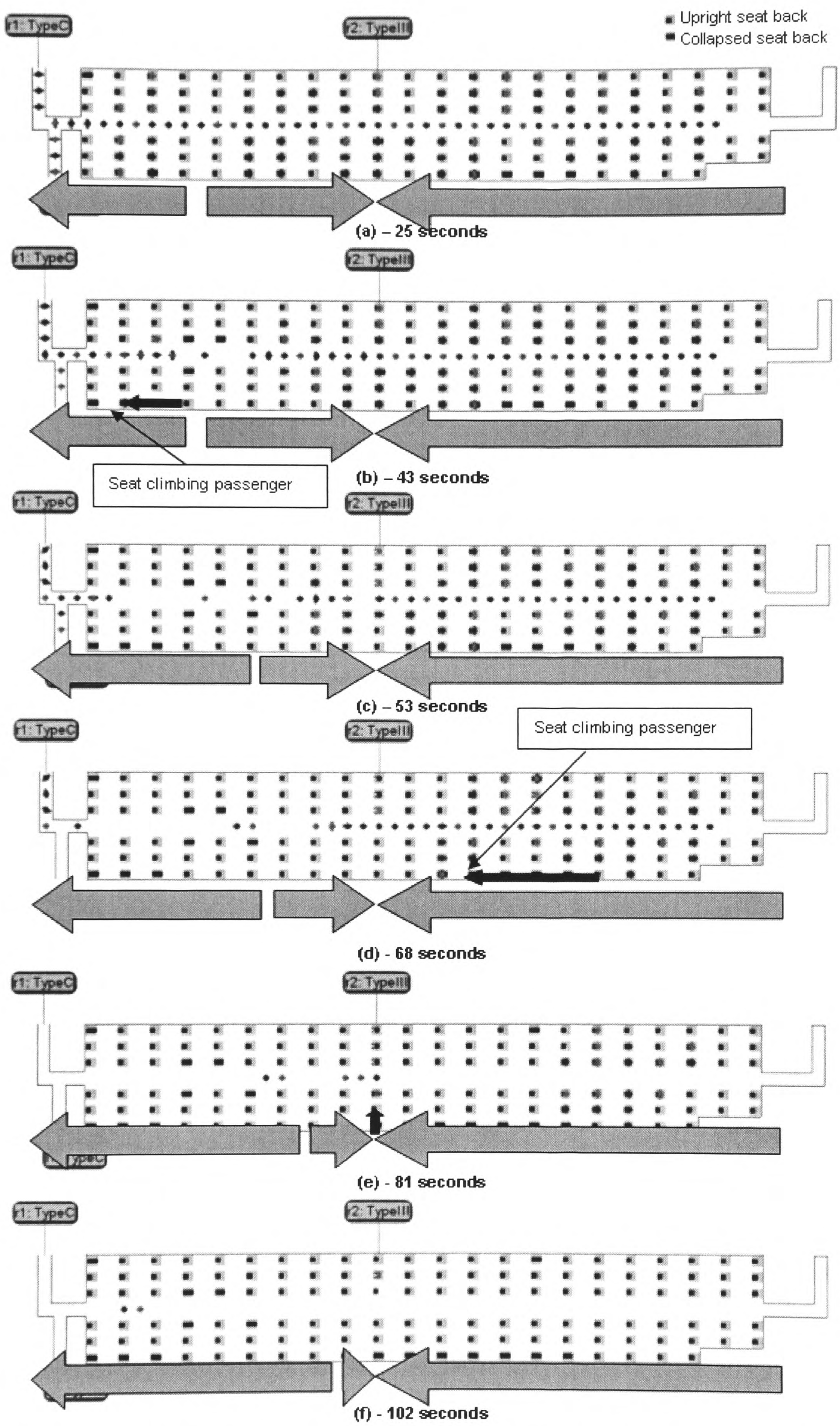


Figure 149: Example evacuation from Scenario 1(a) – Large arrows denote general movement trends – small arrows denote path of seat climbing passengers

8.4.3.3 Scenario 1(b): A full-fire scenario with the Manchester available exits but without exit opening delays

In this scenario the Manchester exit availability is used, however all of the exits will be opened in time representative of that normally achieved in full scale certification trials. This section address the question *"Could a disaster be averted if the exits were opened more quickly?"*.

In this scenario on average 91 passengers successfully evacuated within 109 seconds and 40 passengers died mainly from radiative heat. During the evacuation on average 8 passengers decided to climb seating and each climbed an average of 3.6 rows - the pattern of collapsed seating is depicted in Figure 151(a). The average personal evacuation time of passengers in this case was 42.2 seconds with passengers spending on average 63% of their time stationary due to congestion. Whilst lower this indicates that congestion still exerts a significant effect on the evacuation time of the aircraft. Not surprisingly opening the exits more quickly has decreased the average personal evacuation time by some 15.7 seconds. The death locations can be seen in Figure 151(b). Whilst the swifter opening of the exits reduced the number of fatalities by some 35% on average 40 passengers still died mainly from excessive exposure to radiative heat.

Once again to demonstrate the complexity of the passenger behaviour in this scenario, we will consider one of the 1000 repeat simulations (see Figure 150). It can be seen that initially passengers choose to use their nearest exits (indicated by the solid grey arrows in Figure 150(a)). However, the forward exits quickly exhaust their supply of passengers (see Figure 150(b)). As before the crew are unable to convince passengers to turn around and they only begin to do so as they themselves decide that the forward exits are empty and that their personal evacuation will be reduced by redirecting. Figure 150(c)) shows some of the passengers at the periphery of the R2 exit queue beginning to redirect themselves towards the forward exits. It is noticeable that some of the seats are already collapsed and that passengers are climbing over seating in order to circumvent the congestion in the aisle (see Figure 150(d) and (e)). Eventually, all of the passengers in the forward section decide to move towards the forward exit in the forward section (see Figure 150(f)), however by this time many of the passengers in the aft cabin section being to perish as the cabin nears flash-over.

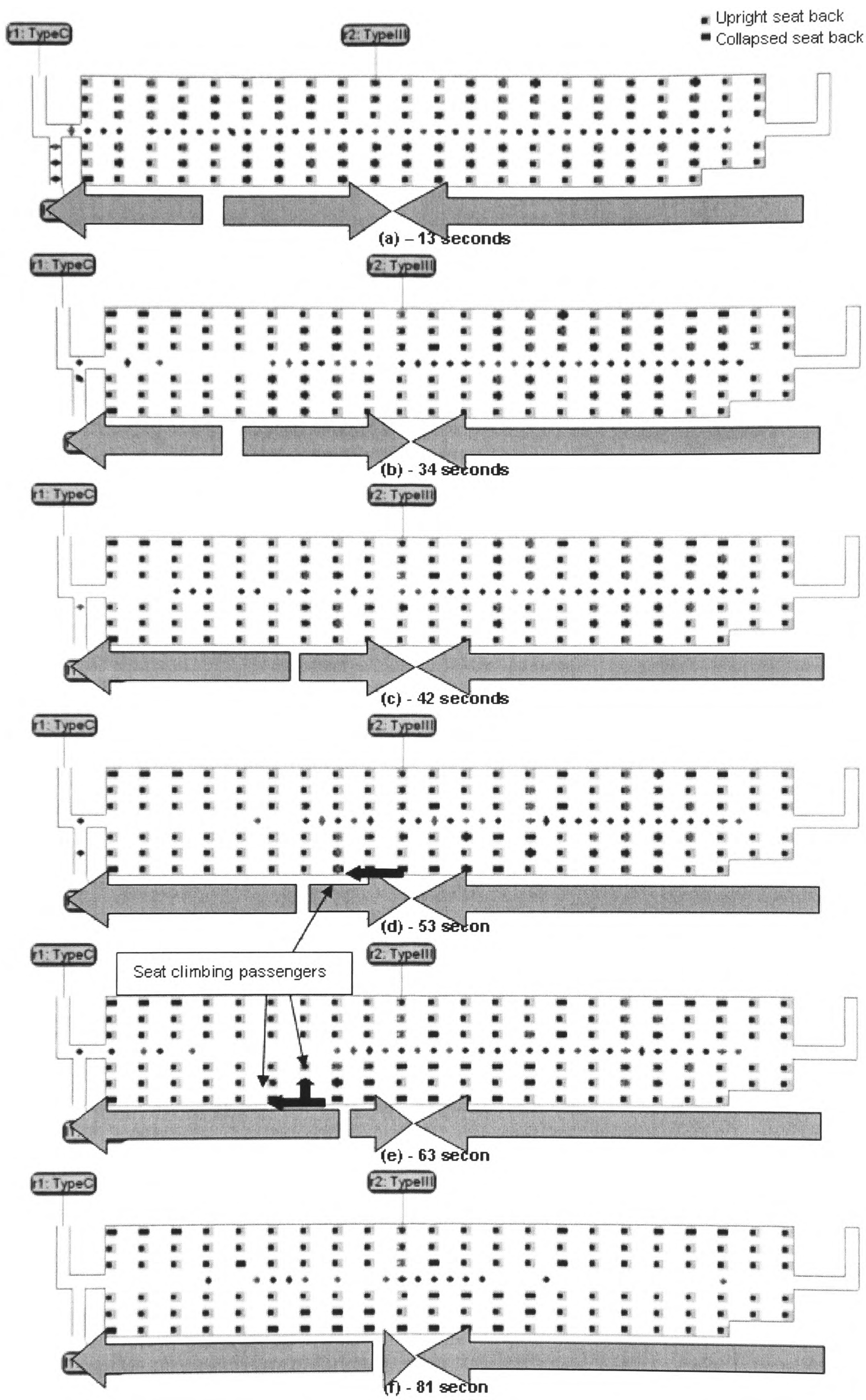


Figure 150: Example evacuation from Scenario 1(b) – Large arrows denote general movement trends – small arrows denote path of seat climbing passengers

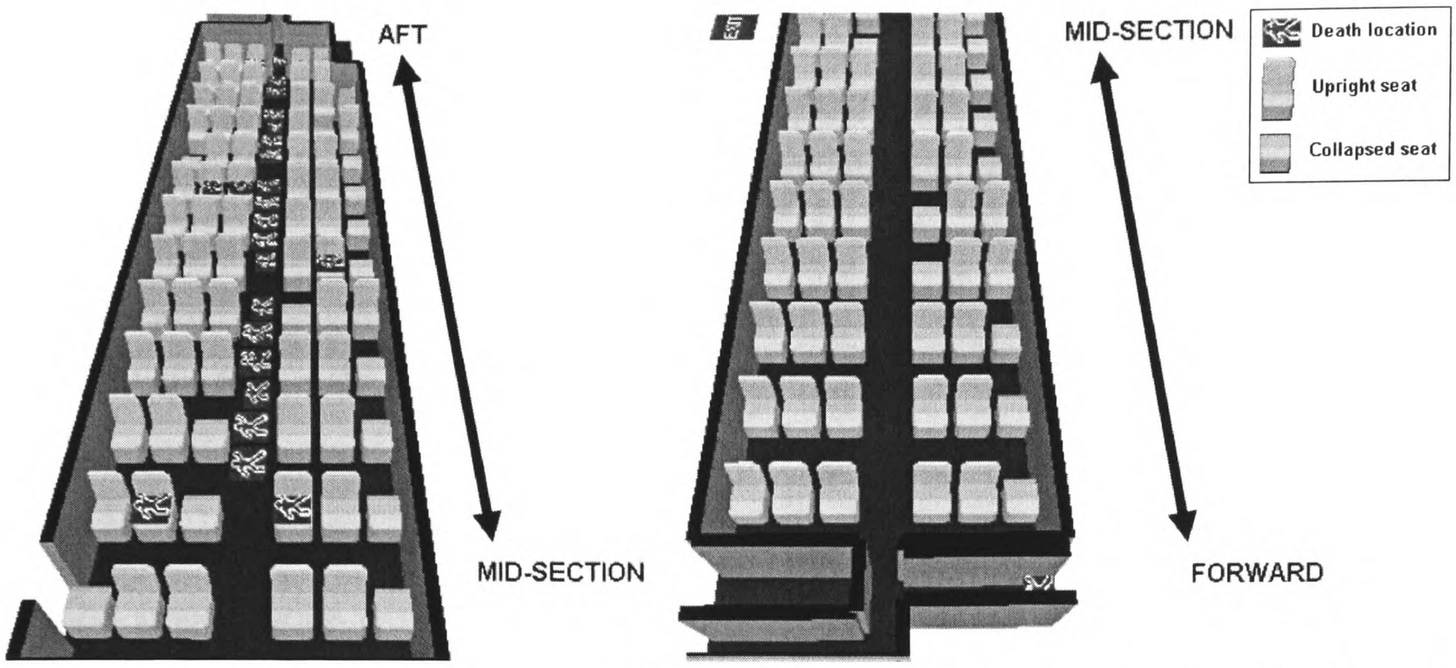


Figure 151: Example VR output from an airEXODUS simulation the location of collapsed seating and the corpse locations from Scenario 1(b)

Table 81: Summary of the results of Scenario 1(b)

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 1(b)	min	88.8	38.1	23.9	2.0	1.2	31.0	0.02
	mean	109.3	42.2	26.6	8.0	3.6	39.7	0.19
	max	122.6	46.1	29.7	17.0	7.0	46.0	0.41
	STDEV	9.2	1.7	1.1	2.6	1.0	3.1	0.10

The results of this scenario (i.e. for the type of fire scenario investigated and the aircraft configuration examined) suggest that **even** if the exits are opened as quickly as possible some 40 passengers would die and a disaster would occur.

8.4.4 90-second certification trials

These set of scenarios demonstrate the evacuation of this aircraft configuration under 90-second certification trial conditions, i.e. without fire and under compliant conditions. The aim of this section is to establish what could have been learnt about the potential for this accident from the current certification methodology. Some scenarios beyond the current certification methodology are used to demonstrate what can learnt from a more rigorous set of certification trials.

8.4.4.1 Passenger and crew behaviour

The remaining airEXODUS simulations contained in this document simulate evacuation under 90-second certification conditions. In this mode extreme passenger and crew behaviours, such as seat climbing, do not occur. The characteristics of these evacuations are,

- Orderly passenger behaviour of the type found in certification evacuations,
- Each exit being made ready in a representative time derived from past relevant certification tests,
- Crew procedures being very effective when employed, i.e. passengers are compliant and crew make perfect decisions
- No seat climbing behaviour.

Finally since smoke is not present within the cabin in these scenarios the cabin crew will have unimpaired vision when redirecting and will therefore be more likely to make 'good' decisions.

8.4.4.2 Scenario 2: A typical 90-second certification trial

This scenario establishes a base-case for the aircraft under typical 90-seconds certification trial conditions. This scenario answers the question, *"What would a typical 90-second certification trial tell us about this aircraft?"* Since this scenario is of a 90-second style evacuation all of the exits down the right side of the aircraft are operative and those on the left are disabled.

Table 82: Summary of the results of Scenario 2

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 2	min	58.2	32.1	19.3	0.0	0.0	0.0	0.01
	mean	62.2	33.3	20.5	0.0	0.0	0.0	0.10
	max	65.9	34.7	21.8	0.0	0.0	0.0	0.18
	STDEV	1.6	0.6	0.5	0.0	0.0	0.0	0.03

It can be seen that airEXODUS demonstrates that the aircraft would evacuate on average in 62.2 seconds [58.2-65.9 seconds]. This is well within the 90-seconds requirement and demonstrates that the aircraft would easily pass the 90-second test. In this case passengers take on average 33.3 seconds to evacuate the aircraft and spend 61.5% of their time stationary due to congestion. Again this suggests that congestion is a significant factor in their evacuation times. The PETs generated in this case are 24.6 (42.5%) and 8.9 (21.1%) seconds lower than scenario 1(a) and 1(b). It is apparent from these results that the simulated 90-second certification trial tells us nothing about the potential failings of this aircraft configuration in a fire scenario.

8.4.4.3 Scenario 2(a): A 90-second scenario with the Manchester available exits but without exit opening delays

This scenario re-runs the 90-second certification trial however using the exit availability from the Manchester scenario, i.e. FR, FL and ROW exits only (see Figure 142).

Table 83: Summary of the results of Scenario 2(a)

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 2(a)	min	121.0	51.2	37.2	0.0	0.0	0.0	0.55
	mean	133.9	55.6	41.4	0.0	0.0	0.0	0.59
	max	150.2	59.4	45.2	0.0	0.0	0.0	0.65
	STDEV	5.1	1.7	1.7	0.0	0.0	0.0	0.02

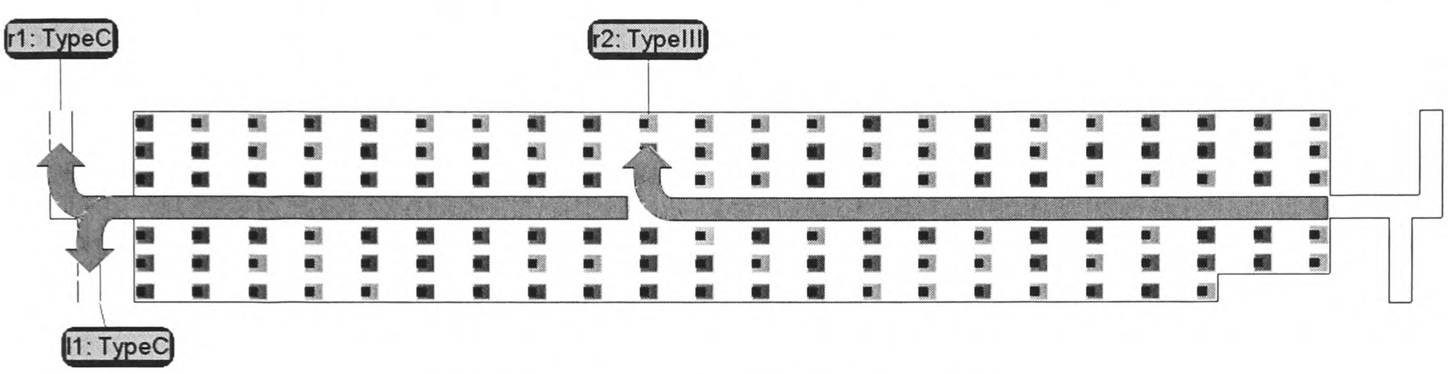


Figure 152: Flow pattern in Scenario 2(a)

In this scenario it can be seen that the average evacuation time has increased to 133.9 seconds [121-150.2 seconds]. In this scenario the relatively high evacuation time results from none of the passengers aft of the Type-III exit being bypassed to the forward exits. The poor exit utilisation is indicated by the very high OPS measure (0.59). However, this scenario is somewhat unrealistic as in a real 90-second certification trial a crew member would likely be positioned at the Type-III exit and be responsible for bypassing passengers forwards when possible. The next scenario simulates this.

8.4.4.4 Scenario 2(b): A 90-second scenario with the Manchester exit availability but without any exit opening delays and with a crew bypassing at the Type-III exits

This scenario repeats 2(a) however a crewmember has been placed adjacent to the Type-III exit and told to bypass passengers forward when appropriate. This represents a more realistic scenario for a 90-second certification trial using the Manchester accident's exit availability (see Figure 153). This configuration is still compliant with 90-second as half the exits are still available.

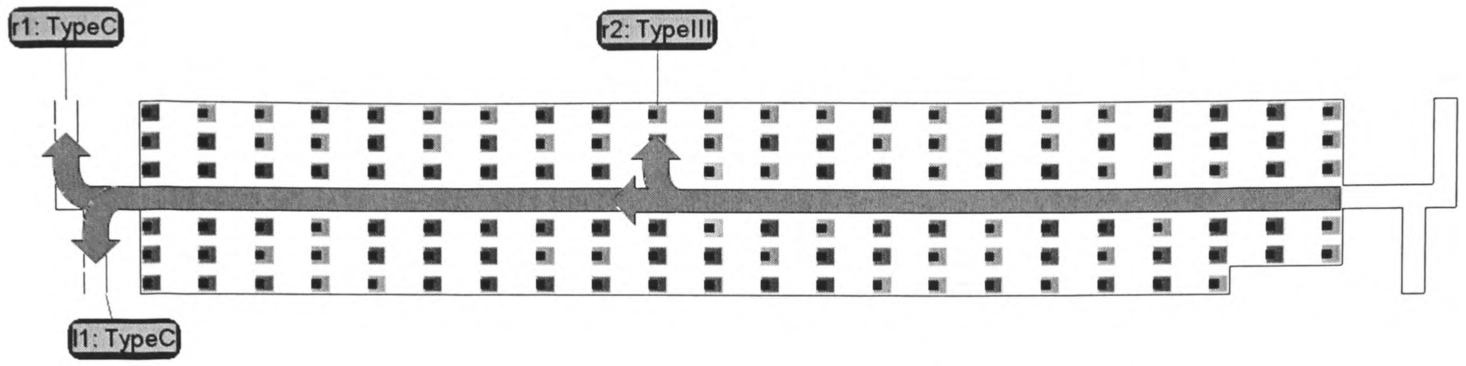


Figure 153: Flow pattern in Scenario 2(b)

Table 84: Summary of the results of Scenario 2(b)

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 2(b)	min	93.2	46.2	30.9	0.0	0.0	0.0	0.01
	mean	101.4	49.8	34.3	0.0	0.0	0.0	0.06
	max	107.5	53.4	37.9	0.0	0.0	0.0	0.15
	STDEV	2.6	1.2	1.2	0.0	0.0	0.0	0.03

It can be seen that all of the simulations generate TETs in excess of 90-seconds. These simulations indicate that this aircraft configuration would fail the 90-second test even with a crew placed adjacent to the Type-III exit and even when the majority of the simulations are optimal, i.e. OPS < 0.1. Thus, **if the manufacturers choose or were forced to certify this aircraft using this exit availability then the aircraft would most likely have failed its 90-second certification trial.**

8.4.4.5 Scenario 2(c): A 90-second scenario with the Manchester available exits and exit opening delays and crew bypass at the Type-III exit

This scenario demonstrates a more rigorous certification scenario in which the exit openings have been delayed as they were in the Manchester accident. In addition exit availability has been set to that which occurred in the Manchester accident. As in Scenario 2(c) a crewmember is located adjacent to the Type-III exit and is responsible for redirecting passengers between the forward and overwing exits.

Table 85: Summary of the results of Scenario 2(c)

		TET (seconds)	PET (seconds)	CWT (seconds)	Seat jumpers (pax)	Rows jumped (rows)	Fatalities (pax)	OPS
Scenario 2(c)	min	121.7	72.6	57.0	0.0	0.0	0.0	0.00
	mean	128.3	75.3	59.7	0.0	0.0	0.0	0.04
	max	135.9	80.0	64.4	0.0	0.0	0.0	0.10
	STDEV	2.9	1.6	1.6	0.0	0.0	0.0	0.02

It can be seen from Table 85 that the average evacuation time increases from 101.4 seconds to 128.3 seconds when exit opening delays similar to those in the Manchester accident are imposed. This scenario demonstrates that in an even more rigorous certification scenario the aircraft would catastrophically fail the 90-second certification test.

8.4.4.6 Main findings

This study has used some of the latest airEXODUS model functionality to simulate an accident scenario similar to the Manchester accident in 1985. In doing so the predicted results were similar to the Manchester accident and predicted a disaster scenario in which over 60 passengers died. Conventional understanding of the accident is that the exit opening delays were a contributing factor in the high number of fatalities. Consistent with this, the model predicted fewer fatalities (approximately 40) when the exits were opened in an amount of time typical to 90-second certification trials. However, despite the number of fatalities being reduced, on average some 40 deaths still occurred and a disaster was still predicted.

This study then examined the 90-second certification scenario(s) that could have been performed on this aircraft configuration in an attempt to establish what could have been known about this accident prior to a disaster occurring.

The model predicted that in a 'typical' 90-second certification scenario, i.e. the 50% exit availability criterion is met by disabling one exit from each exit pair, the results of the model indicated that the aircraft would easily satisfy the 90-second certification trial requirement and could be evacuated in under 90-seconds. Indeed, the model indicates that the aircraft would perform very well at this test, with all of the evacuations begin completed with over 20 seconds to spare. In addition, in a typical 90-second scenario the aircraft demonstrates the desirable characteristic of not requiring crew procedures. Based on this assessment one could draw the conclusions that the aircraft is a good example of "safe" aircraft design.

However, these conclusions could be very different had the aircraft manufacturers not chosen the *optimal* exit availability for the 90-second test. Scenario 2(b) demonstrated that without changing the design or passengers load, but by simply meeting the 90-second exit availability requirement in a different way (2 forward exits and one overwing) the average evacuation time is increased to 101.4 seconds and the aircraft would fail the certification trial. This occurs even if cabin crew procedures are employed at the Type-III exit. Thus, indications of the potential problems during emergency evacuation (as indicated by the simulated fire scenarios and the Manchester air accident) could have been gained had aircraft regulations insisted upon an evacuation demonstration using less than optimal exits.

The results of these scenarios are concerning as they, a) indicate the sensitivity of the 90-second certification scenario to experimental variables especially exit availability, and b) show that the practice of aircraft manufacturers choosing the optimal exits for the trial can lead to over confidence in an aircraft design and hide potential evacuation deficiencies.

Indeed the results of this study demonstrate that had a more rigorous certification methodology been employed the potential problems that this aircraft had during evacuation could have been discovered before the Manchester disaster. However, uniformly choosing any one configuration to test in a 90-second certification trial is a difficult task. In addition, the danger with choosing only one test scenario is that designs become overly specialized towards meeting the single test and loose the ability to perform well in a variety of scenarios. That said, given that the estimated cost of a 90-second certification trial is $2 million (US) [1] performing more than one would prove extremely expensive. In this context the benefits of evacuation modelling become apparent.

8.5 Concluding remarks

This chapter has demonstrated how the technologies developed during this thesis can be used to better understand regulations and to improve the design of future passenger aircraft. In addition, this chapter demonstrated how the technologies developed in this work could have been used to predict a major aircraft disaster. This chapter provides compelling evidence of the appropriateness of evacuation modelling as a tool for the assessment of safety in passenger aircraft.

9 Conclusions

The objective of this thesis has been to advance the development of evacuation-modelling technology, making it better suited as a viable tool for regulatory applications and the safety assessment of passenger aircraft. First this thesis addressed the question *"Are there models appropriate for certification and accident applications. If so what are they and what are they lacking, what needs to be done?"* None of the reviewed evacuation models were deemed to satisfactorily address the necessary evacuation factors. Of those reviewed the airEXODUS evacuation model was the most developed as a tool for the safety assessment of passenger aircraft. As such it was selected for development and subjected to greater scrutiny and evaluation. This revealed the following three key questions that needed to be answered; *"Can the results of this model be trusted, verified and interpreted?"*, *"How can the results and behavioural capabilities of the model be improved?"* and finally *"Can the behavioural capabilities of the model be extended to cover the range of behaviour witnessed in real accidents scenarios?"*

Each of these questions was tackled in turn within this thesis and in doing so evacuation modelling technology advanced. It should be noted that the questions that were highlighted are general failings in the field of aircraft evacuation modelling that serve to hinder the progression of this technology in becoming viable tools for the certification and design of passenger aircraft.

The first question addressed in this thesis was *"Can the results of the model be trusted, verified and interpreted?"*. Issues associated with this question were tackled through undertaking the most comprehensive validation assessment of any evacuation model applied to the field of aviation evacuation modelling to date. In doing so it was recognised that whilst validation will never prove a model correct, confidence in the model's predictive capabilities will be improved, the more often it is shown to produce reliable predictions. This thesis has added an additional six test cases to the list of validation already undertaken on airEXODUS. These cases showed that the model is capable of successfully reproducing the overall evacuation performance of both wide-body and narrow-body aircraft under certification conditions. Using the mean of the airEXODUS generated total evacuation time distributions for each aircraft and the single time achieved by the aircraft in each of the trials to represent the typical evacuation performance, airEXODUS was shown to be capable of predicting the total evacuation time to within *5.3%* or *3.8* seconds. It was also shown that in most cases the model is able to reliably predict the likely evolution of the evacuation from its start to its completion. However in one case the model was unable to accurately reproduce the results of the certification trial as this particular trial involved significant intervention by the crew. This presented difficulties as airEXODUS lacked a predictive model for crew instigated passenger redirection.

This was a significant finding as in most 90-second evacuations the outcome is highly dependent upon the presence and behaviour of cabin crew. Prior to this thesis the standard version of airEXODUS contained an implicit representation of cabin crew procedures. Whilst providing some basic functionality, the representation of cabin crew procedures was limited. Furthermore, prior to this thesis the 'extreme' passenger behaviours contained within airEXODUS were simplistic and based on passengers assessing conditions in their immediate vicinity (i.e. adjacent nodes). Both of these aspects of the behavioural capabilities of the model were extended in this work.

Before answering the two remaining key questions of this thesis, namely "How can the results and behavioural capabilities of the model be improved?" and "Can the behavioural capabilities of the model be extended to cover the range of behaviour witnessed in real accidents scenarios?" some sub-questions needed to be resolved.

Whilst the review and critical assessment of aircraft evacuation models gave an indication of some of the capabilities that evacuation models were lacking it provided little supporting evidence for their development. Thus, two key issues remained. Firstly, *"What evidence can be collected to support the development of new behaviours?"* and secondly *"How can we better understand the processes involved in all of these behaviours?"* To answer these questions an investigation of behaviour exhibited in 90-second certification trials and real emergency evacuations was undertaken. This revealed that cabin management procedures were nearly always employed during certification trials and indeed quite often during real emergency evacuation scenarios.

This suggested that in real emergency evacuations cabin crew instigated exit bypass or redirection occurs with varying levels of effectiveness. Furthermore it suggested that in significant emergency evacuations passengers' form their own exit choice decisions. This could lead to divergent passenger and crew goals. It was suggested that **crew are generally concerned with maximising exit utilisation and thereby reducing the overall evacuation time for the aircraft as a *whole*** whereas **passengers are generally concerned with attempting to reduce their *personal* (including persons with whom they are attached) evacuation times**. When simulating cabin crew procedures in real emergency conditions the models developed in this work represent the conflicting goals between passengers and crew. Furthermore, it was suggested that the compliance of passengers to crew instructions was related to the severity of the evacuation scenario. In addition the frequency of citations of certain types of redirection, seat climbing and aisle swapping behaviour in air accident reports was found to vary according to the severity of the scenario.

For the purposes of modelling these behaviours it was suggested that the broad trends of behavioural characteristics during emergency evacuation can be categorised into the following three broad behavioural groups: 90-second certification trial behaviour,behaviour involved with non-fire/external fire scenarios, and behaviour involved with burn-through/internal fire scenarios.

Crew centred redirection was frequently witnessed in every category, although its effectiveness differed according to the scenario. In contrast passenger seat climbing was most frequently reported in burn-through scenarios and barely reported in other types of evacuations. Accounts of aisle swapping were absent from non/external and burn-through fire scenarios. However, this was thought to originate from passengers considering it unimportant when completing post-accident questionnaires.

The principle mechanisms that are involved in these behaviors were, the collection of information, the processing of the information, and then the actioning of any decision based on the above, and were similar across the three scenario categories. However, the effectiveness and outcome of each aspect varies according to the scenario/category. The models that were developed were based on these three processes and were influenced and varied according to the type of scenario. This approach enabled the trends of the three scenarios to be modelled accurately.

This original analysis provided a framework for addressing the two remaining key questions of this work, i.e. *"How can the results and behavioural capabilities of the model be improved?"* and *"Can the behavioural capabilities of the model be extended to cover the range of behaviour witnessed in real accidents scenarios?"*. Based on the analysis of human behaviour this thesis developed new algorithms capable of simulating crew instigated passenger redirection procedures during 90-second and real emergency evacuations and linked them to algorithms for passenger exit and passenger route optimisation strategies, such as seat climbing or aisle swapping. Within these models passengers were made to be compliant and thus follow all instructions issued by cabin crew when modelling certification evacuations. Whereas in real emergency evacuations more complex features were developed that made passengers more likely to determine their own exit choice.

The investigation of human behaviour in aircraft accidents indicated that both passenger and crew decisions are based on situational awareness, i.e. information that is obtained from the environment during the evacuation, and known aspects of their environment. Mechanisms were provided within the models for passengers and crew to gather both types of information. Primarily this was achieved through a rudimentary implementation of sight, based on restrictions from the geometry of the structure and the smoke conditions within the cabin. The resulting algorithms were employed within airEXODUS and were demonstrated using various certification and emergency evacuation scenarios.

Having extended the functionality of the model the thesis concluded by answering the question *"How could evacuation modelling technology be used? What are the benefits of the techniques developed in this work"*. To address this question this thesis explored some current problems in the safety aviation industry. Firstly, this thesis demonstrated the relative success of the airEXODUS evacuation model in predicting the outcome of previous 90-second certification trials and made a compelling argument of the suitability of the model for evacuation certification applications - at least for derivative aircraft. Recall that in one case the model had difficulty in accurately reproducing the results of a particular 90-second trial. The cabin crew redirection models developed in this work improved the outcome of the simulation of this certification trial.

In addition to demonstrating the models use for certification applications, the final chapter demonstrates the application of the models developed in this work to various non-certification applications through performing three original studies. The first study describes an investigation into a current aviation regulation (the maximum exit separation FAR (i.e. 25.807 (f) (4))) using evacuation modelling techniques. *This study suggested that it is not advisable to mandate a maximum exit separation without taking into consideration exit type, exit availability, occupancy load and aircraft configuration.* Indeed many other factors apart from evacuation time under the current FAR 25.803 evacuation scenario should be considered when determining maximum exit separations. For instance, passenger disability, the presence of fire and smoke, the orientation of the aircraft, reduced passenger numbers, in addition to the parameters already identified are important parameters that need to be taken into consideration. Indeed, severe accidents, smoke and fire could slow the travel speeds of passengers whilst impact damage could reduce the number of passengers that are evacuating. In this type of scenario the maximum exit separation threshold could well be below 60 feet. It was suggested that to correctly take all these factors into consideration when designing and approving new aircraft types requires a performance based regulatory environment that takes a **holistic** view of safety rather than the existing **prescriptive** environment. The lack of sensitivity of the current certification methodology to exit separation distance was demonstrated.

The second application of the techniques developed in this thesis examined evacuation issues for future aircraft design, such as the A380 or the proposed BWB aircraft. This work demonstrated how design and procedural aspects of future aircraft design could be evaluated using evacuation modelling technology. Using the technology developed in this thesis designs were tested quickly, inexpensively and safely. This demonstrates the potential cost saving to aircraft designers and regulators when using the techniques developed in this work in a design context.

A major finding of the VLTA study was that when evacuating passenger via only one deck, the width of the stairs was not the only limiting factor in evacuating passengers quickly. Indeed, the steady supply of passengers to the stairs was a determining factor in the operational flow rate of some stair configurations. As such the number of passenger aisles that fed into the stairs was found to significantly affect the performance of staircases and the evacuation efficiency of some aircraft designs. A conclusion of this study was that centrally located stairs could lead to a more steady supply of passengers to the stairs. With respect to BWB designs under certification type conditions, it was demonstrated that gaining access to the exits at the rear of the aircraft could be an issue in scenarios that involve only rear exit availability. It was suggested that additional longitudinal cross-aisle could help to alleviate this problem. Furthermore, when considering a traditional certification type application in which only one side of the aircraft's exits were available, it was found that the depth of the aft cross aisle was a significant factor in the evacuation of the aircraft. In addition persuading passengers to bypass local exits could be an important activity for crew.

Finally this thesis demonstrated how the technology developed could be used to simulate and then predict a Manchester type aircraft disaster resulting in over 60 fatalities. In part this study demonstrates the importance of the new techniques developed in this thesis for simulating real accident scenarios. In doing so evacuation modelling techniques substantiated some of the established causes of the fatalities associated with the Manchester accident. The techniques developed in this thesis were also used to simulate a series of certification type scenario(s). These scenarios, while extending the current certification process are in-line with the philosophy currently employed. These demonstrated that potential problems could arise during emergency evacuation situations involving a less than optimal exits. The results were concerning as they, a) indicate the sensitivity of the 90-second certification scenario to its assumptions especially the assumed exit availability, and b) showed that the practice of aircraft manufacturers choosing the optimal exits for the trial can lead to over confidence in an aircraft design and hide potential evacuation deficiencies. The results of this demonstrate that a more rigorous certification methodology employing computer simulation are capable of highlighting potential problems with aircraft designs and procedures. In this context the benefits of evacuation modelling become apparent.

In conclusion, this thesis has advanced aircraft evacuation modelling technology through:

- Providing greater confidence in the ability of computer models to simulate 90-second certification trials. This results from the development and also from the extensive validation that was undertaken within this work.
- Developing improved modelling capabilities when simulating the behaviour of passengers and crew in real emergency evacuations. This results from the behavioral enhancements developed in this work based on original research into aircraft accident scenarios situations.
- Demonstrating how the technology developed in this thesis can be applied to address real issues in aviation safety and regulation. The results of three original studies undertaken within this work demonstrated how new understanding can be gained in the regulation, design and safety assessment of passenger aircraft.

9.1 Future work

Looking beyond this work towards future development of evacuation modelling technology it is first apparent that more model validation is required. Whilst validation of airEXODUS V3.0 has been undertaken in this thesis it is a recommendation of this work that additional validation exercises be undertaken.

With respect to future model development the following items are considered important.

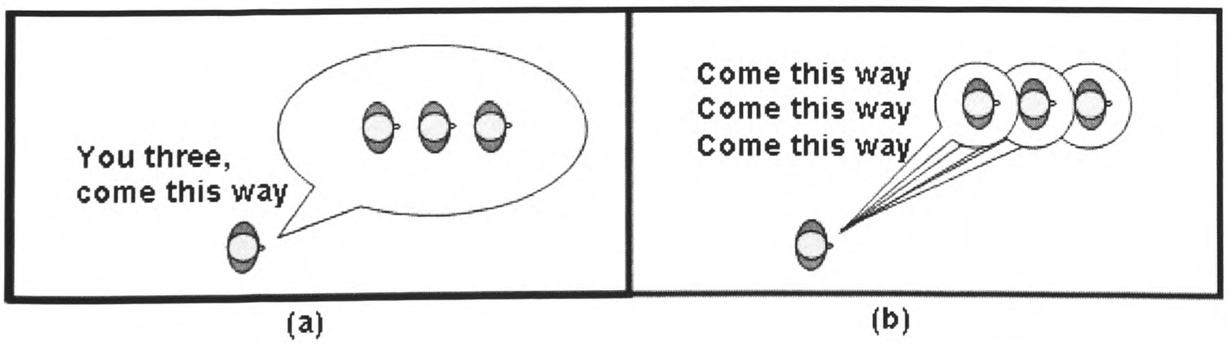


Figure 154: A crew communicating to (a) three passengers as a group, and (b) each passenger individually

This work developed a model that allowed cabin crew to assess and communicate redirection instructions to a single passenger at once - multiple passengers were redirected by successive redirection assessment and instructions being issued (see Figure 154(b)). The next stage of model development should include the redirection and assessment of multiple passengers simultaneously (see Figure 154(a)). This could be achieved using the algorithms developed in this thesis with relative ease.

At present the crew find the passenger best placed for redirecting from the one door to another. This is achieved via the crew ranking each passenger according to the time it would take them to reach the new exit. Within the current algorithms the crew proceeds to instruct the best placed passenger once a benefit to evacuation is noted. The model could be adapted so that instead of instructing the passenger at this point the crew assess the worth of redirecting other adjacent passengers before communicating any instructions. In essence the crew would be building a mental list – or group – of passengers that could be communicated with. Once the crew has a group of sufficient size a group redirection command could be issued.

It is apparent that this adaptation can be accomplished relatively easily using the methods developed within this thesis. However, as with the models developed in this thesis the difficulty is in gaining empirical / scientific understanding of the mechanisms involved sufficient to justify the model.

Whilst every attempt has been made to empirically or scientifically determine parameters used within the models developed in this work current research is limited and as such some approximations were required. Future effort should be focused at better quantifying the parameters used within these models. This relates to the communication effectiveness and range of cabin crew communication and passengers' response to their instructions. Some research into the temporal aspects of communication to single and multiple passengers would also be of benefit.

An important finding of this work and an assumption of the passenger redirection model was the premise that **passengers are not as able to distinguish between the flow characteristics of exits**. Initially this leads to passengers moving towards their nearest exits and later exits with shortest / faster moving queues. A research study into this area would greatly benefit both evacuation modelling and aircraft safety.

The passenger redirection model allows passengers to consider what is best for them personally. This trend has been shown in accident analysis undertaken in this work using the AASK database. In reality passengers would not just be concerned with themselves but also others with whom they are emotionally attached. Future work should be directed towards adapting the models developed in this thesis so that a strongly bonded group of passengers such as a family consider what is best for the group. Again this could be achieved relatively easily using the methods described in this work and previous model development [52]. Using the 'Gene' concept [52] family groups could be defined and their decision making based on the capabilities of the whole group. This may involve adjusting some personal calculations to take account of the slowest moving passengers in any group. In addition individual redirections could be replaced by one redirection for the entire group.

Once again, the algorithms developed in this work can be adapted to cover these features. As before the difficulty arises in gaining sufficient empirical understanding of the process to justify the resulting model.

Finally, whilst some capabilities were provided to cover behaviour in smoke filled environments more work is required. In this context the models that have been developed in this work represent a first stage of developing behaviour in these types of environments. For example, within these models passengers and crew consider smoke as presenting an obstacle to movement, i.e. slowing movement, but do not consider likely death from smoke/fire as an obstacle to movement. Insufficient data was available within AASK to justify the inclusion of these features.

Within the current prototype model when vision becomes obscured either by monuments or smoke conditions passengers and crew do not have any information about conditions in non-visible areas even when they have recently left the area that is non-visible. Providing passengers and crew with a form of memory would allow then to make decisions based on previous experiences onboard the aircraft. Ultimately this would generate more realistic behavioural patterns.

For most of the features proposed for further development, a better understanding of actual passenger and crew behaviour is required. This can be achieved through better targeted full-scale evacuation experiments and through more targeted accident analysis. The latter can be achieved through modifying the post-accident questionnaires currently used to debrief passengers and crew by organisations such as the NTSB and AAIB.

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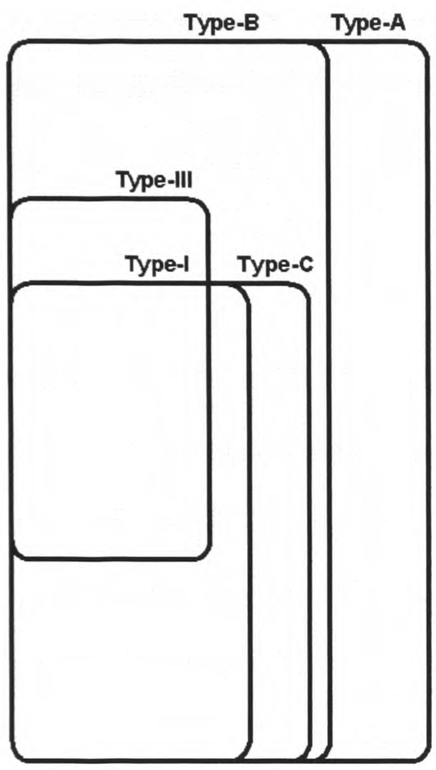
Appendix A

Definitions and terms

Exit types

This section describes the dimensions and flow characteristics for each of the exit types discussed within this thesis.



Exit Type	Minimum Height (inches)	Minimum Width (inches)
Type-A	72	42
Type-B	72	32
Type-C	48	30
Type-I	48	24
Type-III	36	20

Figure 155: Exit type featured in this thesis

The minimum dimensions for the five exit types as specified by FAR are shown in Figure 155. It can be seen that the Type-A exit is the largest followed by the Type-B, Type-C, Type-I and finally the Type-III is the smallest exit considered within this document.

The Type-A exit is a floor level exit with sufficient width to accommodate two passengers evacuating in parallel onto an escape slide with two lanes. Typically a Type-A exit is of sufficient size for passengers to walk through the exit without the need to duck or squat.

By comparison the Type-B, Type-C, Type-I and Type-III exits all have single lane exit slides. Therefore, whist the widths of the exits may vary they are both only capable of evacuating passengers sequentially. The differences in the dimensions of the exits determine the type of negotiating behaviour that passengers adopt when evacuating onto the exit slides.

A Type-B exit is a floor level exit with sufficient height to allow passengers of average height to walk through it without the need to squat or duck. In addition the width of a Type-B exit is sufficient to allow relatively wide passengers to pass.

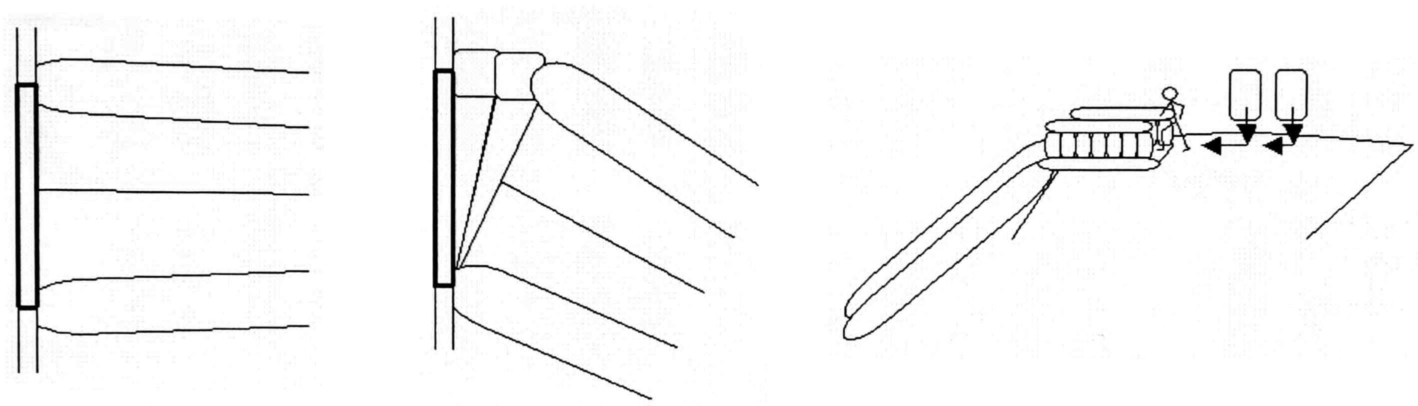
The minimum height of the Type-C and Type-I exit is such that passengers are required to take some form of negotiating behaviour perhaps ducking or squatting as they pass through the exit onto the exit slide. Both of these exits are mounted at floor level.

Passengers evacuating through the Type-III exits have to negotiate a step up to exit itself followed by a step down onto the wing of the aircraft. In addition the minimum dimensions of a Type-III exit are comparatively small. Passengers evacuating through a Type-III exit are required to employ significant negotiating behaviour in traversing this type of exit.

In addition to differences in the minimum size of exits there are differences in the type of escape system employed at the exit aircraft. One variation is the overwing exit, see Figure 156(c). The overwing exit evacuates passenger onto the aircraft wing. Once on the wing passengers typically walk towards the trailing edge where an inflated slide is positioned ready to evacuate them onto the ground. As passengers are not required to jump from overwing exits onto an exit slide - but instead land on the relatively flat surface of the wing - it is expected that the exit flow rates of overwing exits would be different to non-overwing exits of the same type.

Another variation is that some exit slides are sometimes canted, see Figure 156(b). Typically the exit slides of floor level exits extend in a straight line immediately adjacent to the exit, see Figure 156(a). However, in order to meet regulatory requirements it sometimes proves necessary for the slide to be slightly canted, see Figure 156(b). To meet regulatory requirements a small platform – typically 1-2 feet deep – is required linking the exit slide to a floor level exit and serving to rotate the angle of the slide. These types of exits are referred to as canted exits.

The final variation considered within this report is upper deck B747 exits. Since the upper deck of the B747 is 8.1 metres from the ground the exit slides are significantly longer than 'standard' exit slides.



(a) (b) (c)

Figure 156: Three different variations of exit slides: (a) a standard slide arrangement, (b) a canted slide arrangement and (c) an overwing escape system

Exit identification

When discussing the details of AASK the reader should be aware that the authors of the database have designed a generic naming convention for the various exit positions. Usually aircraft exit pairs are numbered 1, 2, 3 etc, but this does not indicate the *relative* position of the exits compared to other aircraft. The convention designed simply makes use of code marking the position of the exit, e.g. Forward (F), Mid-Forward (MF), [Forward/Aft] (for forward and aft overwing exits) Overwing (OW), etc., and a left (L) or right (R) side indicator. Table 86 lists all the possible combinations.

Table 86: Explanation of exit designations used within AASK

Designation	Explanation
FL	Forward Left
FR	Forward Right
MFL	Mid-Forward Left
MFR	Mid-Forward Right
LOW	Left Overwing
ROW	Right Overwing
FLOW	Forward Left Overwing
FROW	Forward Right Overwing

Designation	Explanation
ALOW	Aft Left Overwing
AROW	Aft Right Overwing
LUW	Left Underwing
RUW	Right Underwing
MAL	Mid Aft Left
MAR	Mid Aft Right
AL	Aft Left
AR	Aft Right

Exit locations

In addition two general terms are also used in this thesis to specify the location of exits. End of section exits refers to exits located at the forward of aft extremities of the cabin (see Figure 157(a)). Mid-section exits refers to exits located centrally within the aircraft cabin (see Figure 157(b)). Typically, mid-section exits can be assessed in both the forward and aft directions.

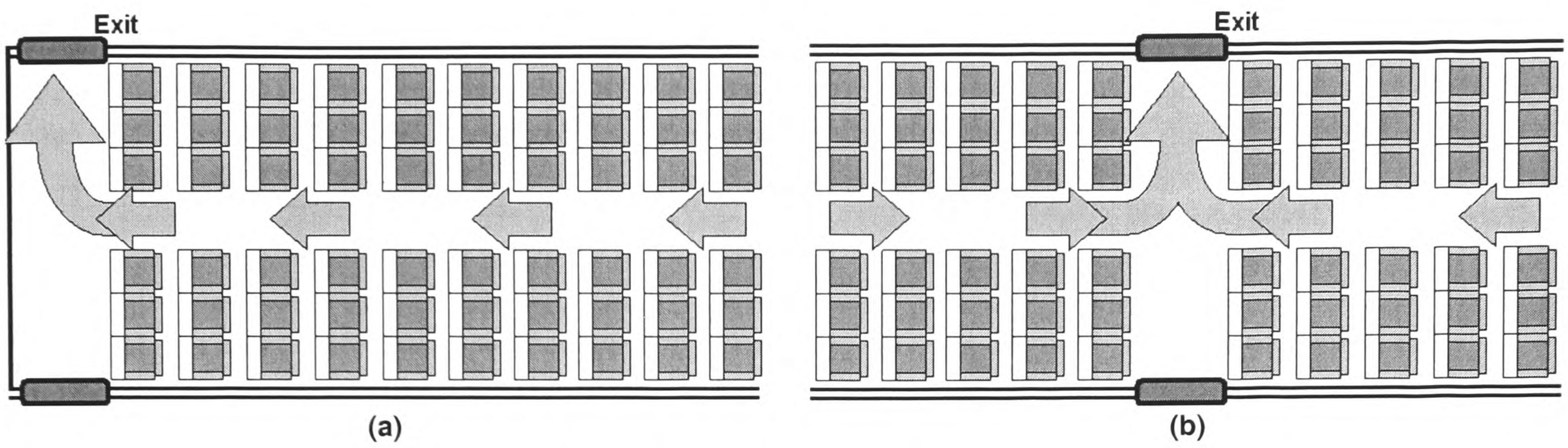


Figure 157: examples of (a) End of Section exits and (b) Mid-section exits

Aisles are referred to as either near or far. Near refers to the aisle that is located nearest to the active and aft to the aisle furthest away. Sometimes the flow direction of the passengers, i.e. forward or aft, is used in conjunction with the near or far terms to distinguish between different areas of the cabin (see Figure 158).

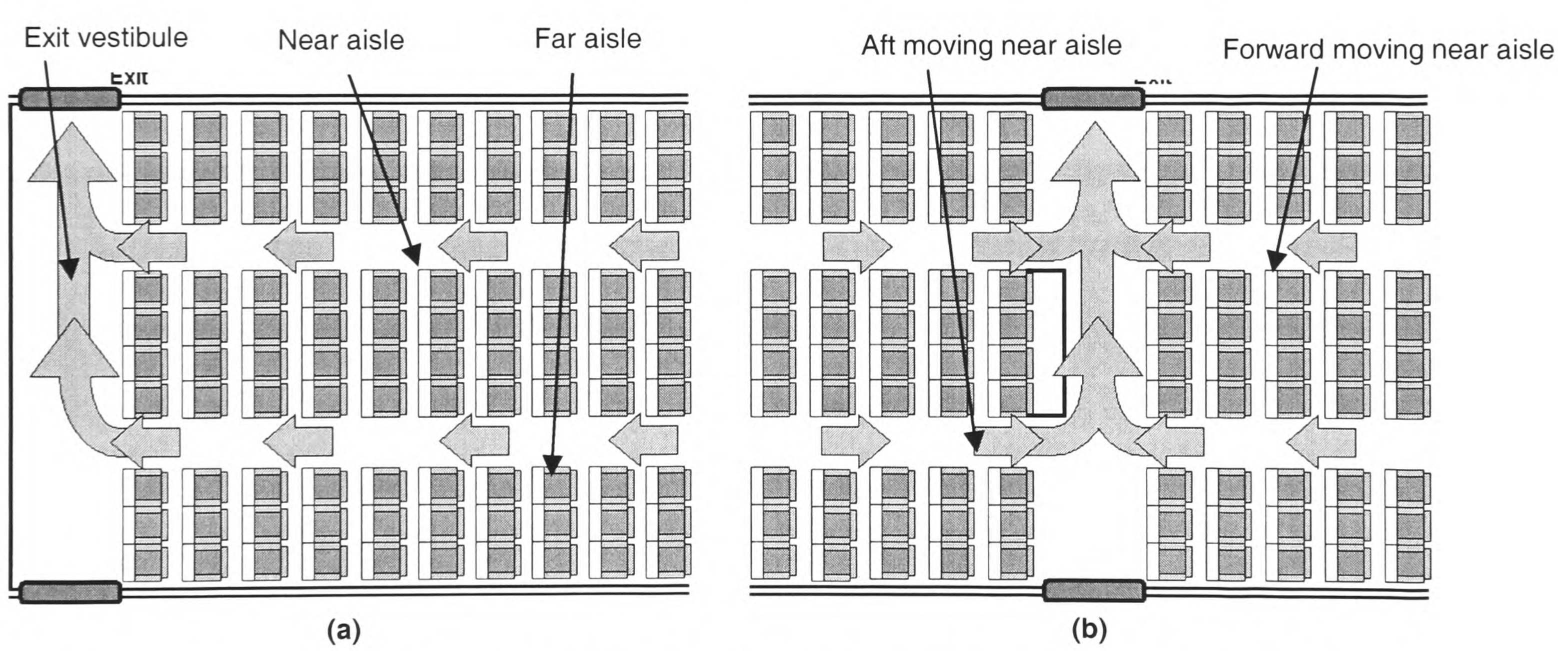


Figure 158: An example of a wide-bodied (a) end of section and (b) end of section cabin section

Appendix B

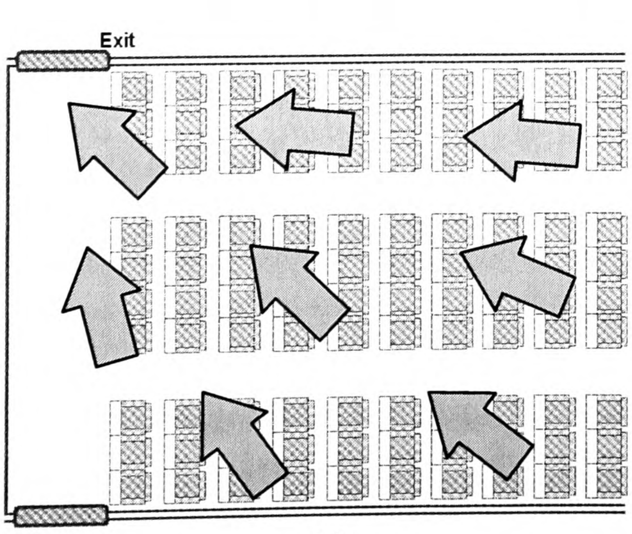
A Component Based Method of Representing Movement within an Aircraft Cabin

At present nodal based evacuation models, such as airEXODUS, calculate a potential map over the entire geometry. The potential map stores the distance of each node/tile from exit(s). Using these maps passenger movement towards the exits are controlled via the simple rule of reducing the potential value of their node/tiles.

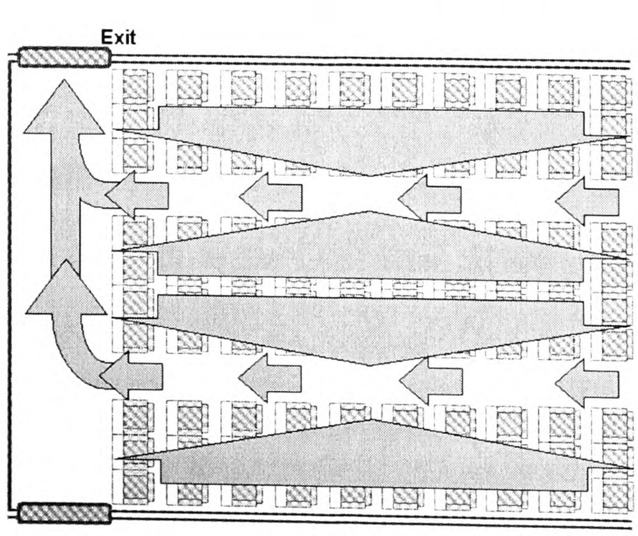
However, in most aircraft passenger movement is not governed by simply reducing their distance from the exit at each movement step (see Table 87(a)). Instead passengers seek to realise a series of more local goals that ultimately lead them to reach to an exit (see Table 87(b)). For example in a wide-bodied aircraft with floor level exits a seated passenger would follow a series of goals such as:

1. move to the nearest aisle, then
2. move to the nearest vestibule/exit passageway, then
3. move to the nearest exit.

Within airEXODUS, this behaviour can be modelled through the use of Attractor/Discharge nodes that are generated by the user prior to simulation. These nodes, allow the user to impose specific potential values on nodes that generate desired movement patterns over regions of the geometry. In wide-bodied aircraft under 90-second certification trial conditions Attractor/Discharge nodes are required in order to make each aisle equally attractive to seated passengers. This is achieved via generating Attractor/Discharge nodes at the point where aisles join vestibules.



(a)



(b)

Table 87: (a) movement pattern assuming a model where passengers simply reduce their distance from the exit and (b) the movement pattern observed in aircraft evacuations

The drawback with their use is firstly that the user must define them prior to simulation. As such there are static throughout the simulation and are unaffected by changes to exit availability. Thus, the desired movement pattern is only generated when the exit availability remains static and passengers follow the regime that they impose. Clearly this is not always the case especially in cases where passengers are making their own exit choice decisions and/or being redirected within the aircraft cabin.

Thus a new system is required that allows more complex behaviour patterns to be generated.

Defining aircraft components

This section details a spatial component-based method of calculating the potential map in which the computer generates realistic potential maps for variations of exit availability.

The method is spatial component based, in other words it uses the spatial accessibility of the structure to determine the movement pattern within the aircraft. As it is spatial component based, it is necessary for the aircraft geometry to be segmented into various spatial components. In aircraft simplistically there are four types of spatial components, namely:

- aisles (A),
- vestibules (V),
- seats (S), and
- seating cross-aisles (X).

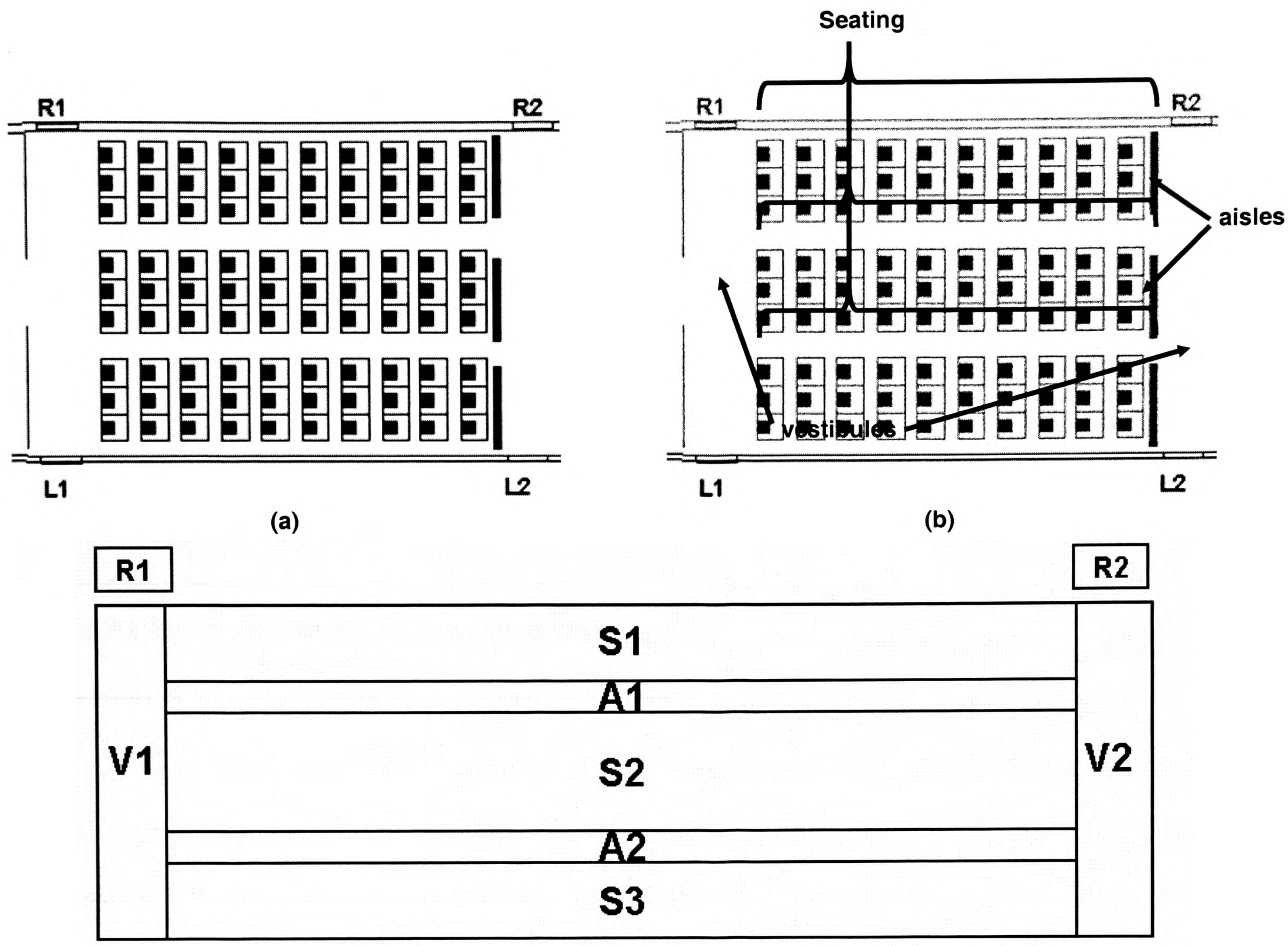


Table 88: an example cabin section (a), and (b) its associated spatial components and (c) a spatial component based model of the geometry

Each spatial component is labelled according to their type (see Table 88(b)). The movement goal of passengers can then be governed by the type of spatial component in which they find themselves, i.e. if in an aisle seek to leave the aisle.

The aim is to allow complex exit choice to facilitate this it is advantageous to store a route potential map for each active exit within geometry. Conceptually a region of space has a unique potential value determined by the route that you are taken through the enclosure. To reflect this each node would have many different potential values that are used according to exit (and associated route) that the passenger is taking (see Table 89). Using the potential values of all of the available exits a global potential map that is similar to nearest exit use can be determined.

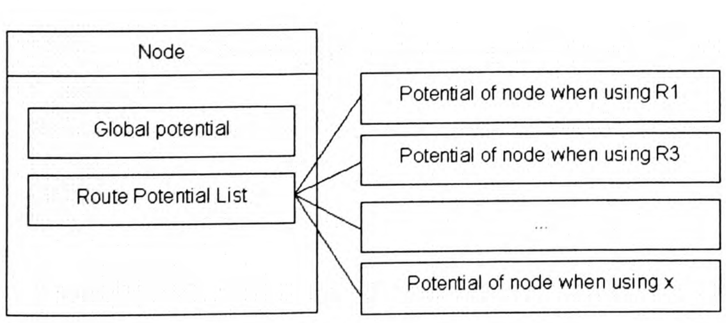


Table 89: Each node has a route potential map as well as a global potential map

The spatial component based-scheme calculates potential maps component by component, taking into account realistic movement patterns within the aircraft. An example of how this is accomplished is demonstrated below. As mentioned previously a potential map is calculated for each exit in turn. The steps involved in calculating a route map for the R1 exit is outlined using the hypothetical cabin section in Table 88.

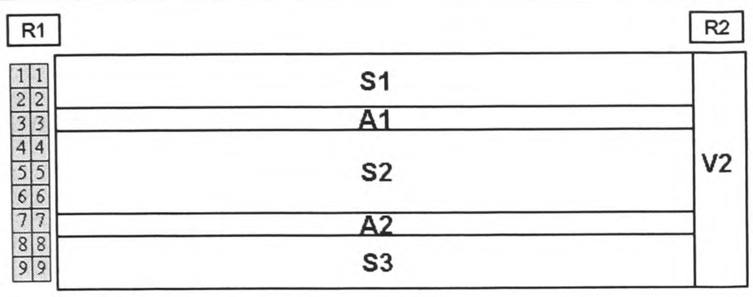


Table 90: Vestibule immediately adjacent to exit is calculated first

The potential is calculated within the immediately adjacent component (see Table 90) to the exit potential map currently being generated. In most cases this would be a vestibule spatial component, however at Type-III exits the adjoining spatial component could be seating (in the case of the initial exit being of Type-III, then the algorithm is initiated at step 2).

1. Firstly, should the adjoining spatial component be a Vestibule then the potential map within the entire vestibule spatial component is calculated (see Table 90).

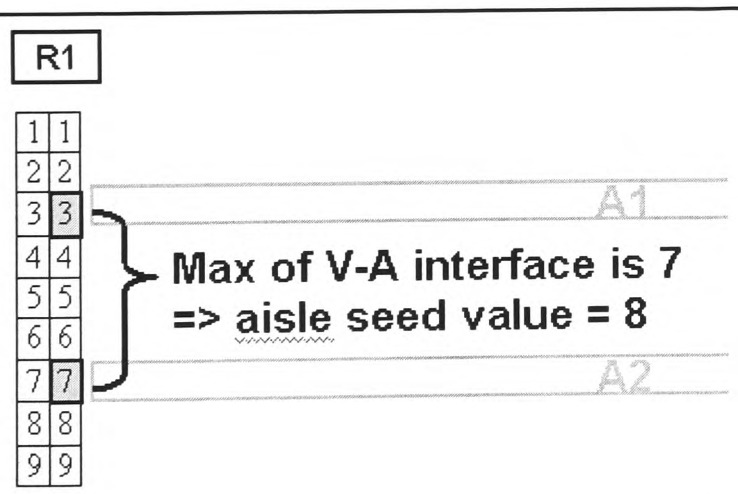


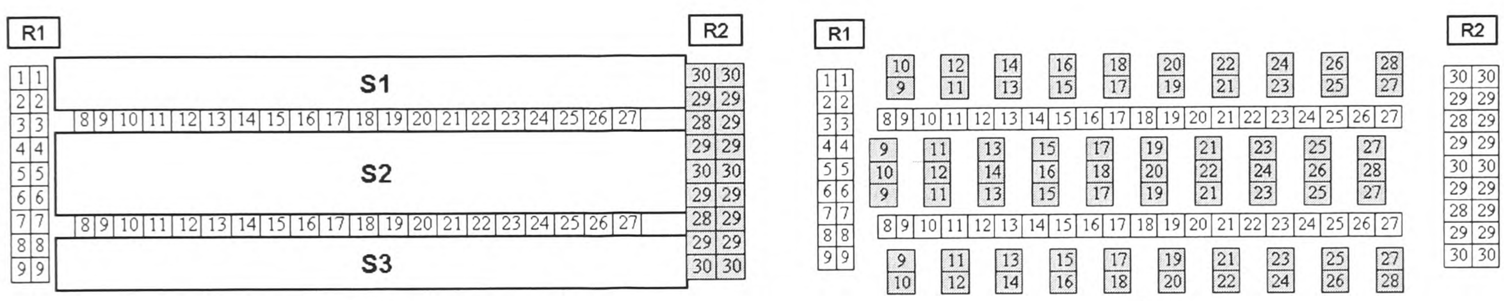
Table 91: Maximum V-A interface seeds connecting aisles

2. Aisles that adjoin the vestibule need to have equally attractive potential values in order to generate realistic behaviour within the cabin. Once the potential of the Vestibule spatial component has been calculated this can be achieved via analysing the potential of the Vestibule spatial component and finding the maximum potential of the Vestibule/Aisle interfaces (see Table 91).

Table 92: V-A interface value is used as seed for adjoining aisles

3. Potential well calculations of adjoining aisles are then seeded with the maximum potential value of Vestibule/Aisle interfaces for the component (see Table 92). Using the seed value for the vestibule, the potential map for the adjoining aisles spatial components are calculated. Should the aisle join other vestibules then step 1 is repeated for the new vestibule component.

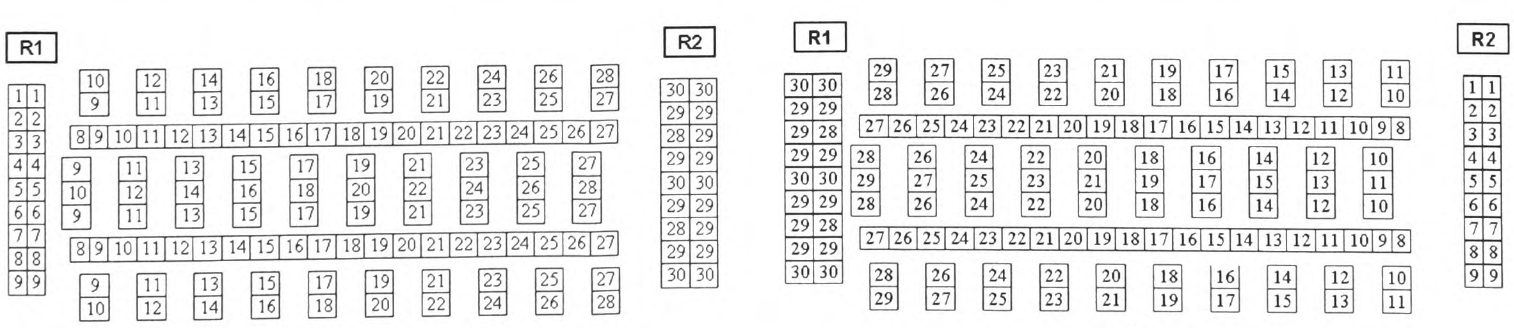
4. Finally the potential values of seats components are calculating using the values of Seat/Aisle and Seat Vestibule interfaces.



(a) (b)

Table 93: (a) Continue into other vestibule spatial components and aisles, and then finally (b) fill in the values of the seats

This process is repeated for each active exit within the geometry (see Table 94). Once all of the route maps have been calculated a global potential map for general movement can be determined by taking the minimum of each node's route potential values.



(a) **(b)**

Table 94: (a) Route map for exit R1 and (b) the route map for exit R2

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Examining the effect of exit separation on aircraft evacuation performance during 90-second certification trials using evacuation modelling techniques

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ABSTRACT

his paper examines the influence of exit separation, exit availability nd seating configuration on aircraft evacuation efficiency and evacation time. The purpose of this analysis is to explore how these arameters influence the 60-foot exit separation requirement found i aircraft certification rules. The analysis makes use of the airEXDUS evacuation model and is based on a typical wide-body rcraft cabin section involving two pairs of Type-A exits located at her end of the section with a maximum permissible loading of 220 ssengers located between the exits. The analysis reveals that there a complex relationship between exit separation and evacuation iciency. A main finding of this work is that for the cabin section amined, with a maximum passenger load of 220 and under certifiion conditions, exit separations up to 170ft will result in approxitely constant total evacuation times and average personal evacuan times. This practical exit separation threshold is decreased to 4ft if another combination of exits is selected. While other factors ist also be considered when determining maximum allowable exit arations, these results suggest it is not possible to mandate a ximum exit separation without taking into consideration exit type, t availability and aircraft configuration.

) INTRODUCTION

bid to increase efficiency and passenger comfort aircraft manuurers are striving to design and build larger aircraft such as the 0. In addition, stretches to existing aircraft aim to gain greater iencies from existing designs such as the A340-600. Even more itious are radical concepts consisting of blended wing body (BWB) design, involving one or two decks and with five or possibly six aisles. This drive for increased efficiency — and hence increased passenger capacity and aircraft size — is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design.

Regulators attempt to enforce and maintain safety standards through a set of essentially prescriptive rules that have evolved over time. In the USA the rules are known as the Federal Aviation Regulations (FAR)[1], while in Europe they are know as Joint Aviation Regulations (JAR)[2]. One of the rules that has evolved over time relating to aircraft evacuation efficiency is the so-called '60-foot' rule. The rule appears in the FAR (i.e. 25.807 (f) (4))[3] and there is an equivalent ruling in the JAR. The FAR rule states;

"For an airplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage, as measured parallel to the airplane's longitudinal axis between the nearest exit edges."[3]

This regulation was introduced into the FAR as amendment 25-67. The origins of this amendment can be traced to a configuration modification to a B747 aircraft. In 1984, Boeing Commercial Airplane Group (Boeing) requested certification for a modification to the B747 that required a pair of exits on the main deck to be deactivated. This resulted in the maximum exit separation increasing from 44ft to nearly 70ft. In deactivating the pair of exits, Boeing also reduced the maximum capacity of the main deck from 550 to 440 passengers in line with the regulations of the day.

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Prior to this request and since 1967, the Federal Aviation Administration (FAA) ! . The FAA had howeve

"...*an exit be* ; *igers, that an exit be loc* *ieans of passenger evacuation, and that exits be distributed as uniformly as practicable taking into account passenger distribution.*"[4]

While the FAA granted the Boeing request, they received many complaints from the public for allowing the deactivation of the exits. After much debate, the FAA introduced amendment 25-67 on June 16 1989[4], setting an arbitrary limit of 60ft to exit separation.

As with most prescriptive rules, amendment 25-67 suffers from the arbitrary nature of its specification. The rule is not founded on any fundamental understanding of evacuation dynamics, accident scenarios or human behaviour. The rule even ignores the nature of the exits (e.g. exit size) that exist at the end of the 60-foot separation.

Intuitively, exit separation is an important parameter in determining aircraft evacuation efficiency. However, before rules can be correctly established limiting exit separation, it is essential to understand how exit separation influences evacuation efficiency. The purpose of this paper is to take the first step in a systematic study of exit separation and evacuation efficiency. Furthermore, the study makes use of the evacuation modelling tool airEXODUS[5-9] to define the scenarios, describe the evacuation dynamics and human behaviour.

As in any experimental or theoretical study involving human behaviour, the numerical results and conclusions quoted in this study are very much dependent upon the scenarios posed, in terms of population abilities, geometry and passenger behaviour. Different evacuation times may result if different parameters and different scenarios are examined. Indeed, it should be noted that this study is restricted to passenger behaviour observed during certification type evacuation conditions. Therefore, while the precise nature of the numerical results are not considered important in themselves, the overall trends in the results are of more importance. As with any computer model, the veracity of the airEXODUS model itself is the subject of ongoing validation exercises[10]. Needless to say, the main conclusions from this study can be substantiated through targeted experimental trials. Finally, the results described in this paper are a summary of a more detailed report[11].

2.0 THE AIREXODUS EVACUATION MODEL

2.1 EXODUS overview

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from complex structures. The EXODUS family of evacuation models currently consists of two distinct packages, buildingEXODUS[9,10] and airEXODUS[5-9]. buildingEXODUS is designed for applications in the built environment and is suitable for application to complex structures such as airport terminal buildings and rail stations. airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation.

The airEXODUS model has been described previously[5-9] and so only the components relevant to this study will be briefly described here. In addition, issues associated with its validation[5-9] and the validation of evacuation models in general[9] have been described previously and will not be repeated here. Suffice it to say that the validation of evacuation models must be viewed as an on-going activity, the more successful validation that is produced, the more confidence we have in the capabilities of the model. Predictions made using the airEXODUS evacuation model have successfully been compared with experimental data and data from evacuation certification trials[5-9].

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The EXODUS software has been written in C++ using object orientated techniques and utilises rule base technology to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules.

2.2 Certification data used in airEXODUS

AirEXODUS makes use of 90-second certification data[13] to specify certain model parameters[6]. In the work presented here, the most important parameter is the passenger exit delay time. This time represents two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit.

In general, the exit hesitation time is due in main to passengers either waiting at the exit for the path to clear and/or contemplating how to negotiate the exit. In either case, the exit negotiation stage does not usually start until there is space for it to commence. Furthermore, the process of passing through the exit and travelling from the exit to the ground are considered as separate events that can occur in parallel.

In the current study we are primarily concerned with Type-A exits. These are floor level exits connected to a slide that are sufficiently wide to allow two passengers to pass through simultaneously. Type-A exits are the largest exits that currently exist on passenger aircraft with a minimum width of 42" and a minimum height of 72"[3]. Here we further assume that the exits are staffed by an assertive cabin crew member.

Within airEXODUS the exit delay time distribution is segmented into subintervals described by uniform distributions. The technique is dependent on the user having a good representation of the actual delay time distribution. In the current version of the software this data is extracted from past certification trials[13]. For the purposes of this study, data corresponding to main deck Type-A exits with assertive cabin crew is required. Suitable data was selected from 11 previous certification tests involving Type-A exits with assertive cabin crew. The aircraft meeting these selection requirements were as follows: A310 (255 passenger), A310 (280 passenger), B747, B747-300, B747-SR, B767-300, B767-346, B777-200 (420 passenger), B777-200 (440 passenger), DC-10 and MD-11[13]. In total, passenger exit delay time data from 20 exits representing some 2,078 paxs is used to define the passenger exit delay time distribution.

2.3 Relevant airEXODUS paramaters

Several airEXODUS parameters will be frequently referred to in this study. These are; personal elapsed time (PET), total evacuation time (TET), cumulative wait time (CWT), response time, exit ready time and the off-time (see Ref. 6 for details).

The TET is a measure of the evacuation time for the aircraft. It is measured from the start of the evacuation to when the last passenger exits the aircraft. A single TET is determined for each evacuation simulation. Perhaps of more interest to an individual passenger is the PET. The PET is a measure of an individual's evacuation time. It is measured from the start of the evacuation to when the passenger has exited the aircraft. A PET is determined for each passenger in the evacuation simulation. The response time is the time a passenger takes to respond to the call to evacuate, release their seat restraint and stand. The response time is an attribute assigned to each passenger as part of the scenario definition.

The CWT measures the total amount of time a passenger has spent in congestion. This is measured after the passenger has completed their response time to when the passenger has exited the aircraft.

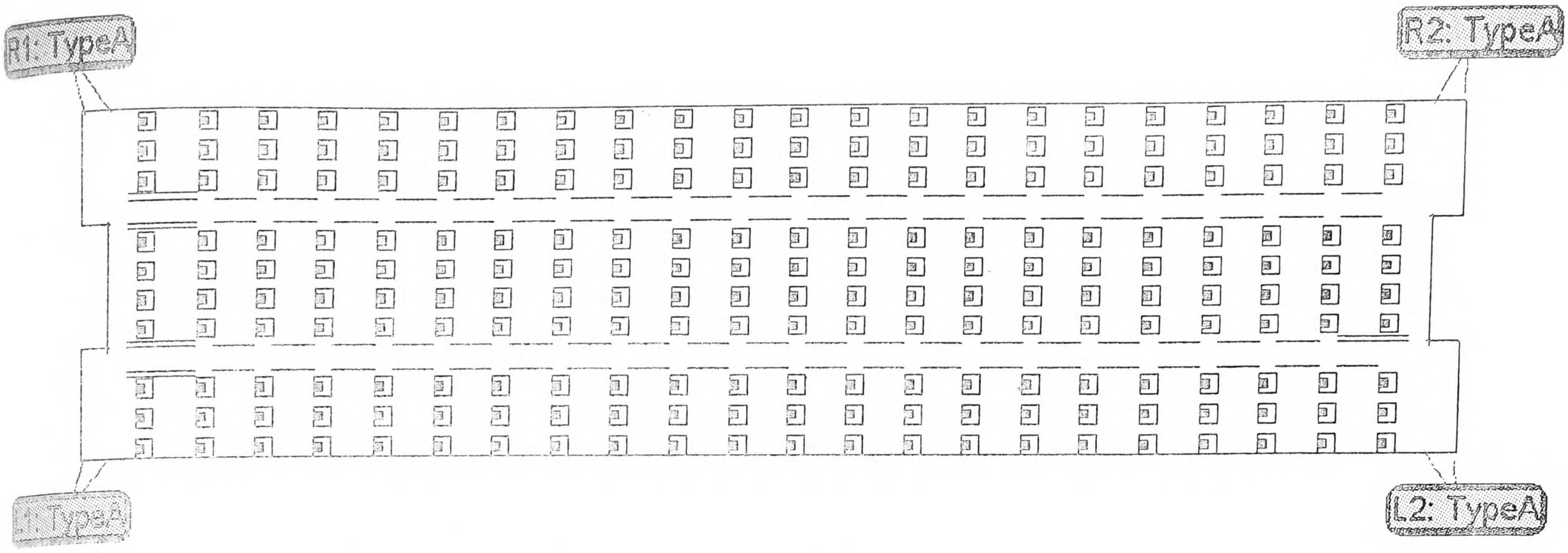


Figure 1. The airEXODUS representation of the base-case cabin section geometry.

This can include time spent in the seat row attempting to get into the aisle, time spent stationary in the aisle and time spent queuing at the xit. A CWT is determined for each passenger in the evacuation imulation.

The exit ready time is the time required for the exit to be opened nd made ready for use. The exit ready time is an attribute assigned o each exit as part of the scenario definition. In these scenarios, the xit ready time is set to 10·7 seconds so as to remove the exit ready ime variable. This time has been derived from the analysis of certifi-ation data[13] and represents a typical time for Type-A exits with ssertive crew.

The off-time (for Type-A exits) is the time required for the passenger) reach the ground once they have mounted the slide. Like the assenger exit delay time, this is derived from certification data. lowever, in the present study, this is taken as zero. If on-ground times re desired, a suitable slide time can be added to the TET.

Finally, airEXODUS is stochastic in nature. This means that very time a simulation is repeated a slightly different evacuation ne will result, as the individual passengers are unlikely to actly repeat their actions. In addition, as the passenger exit lay time is randomly attributed according to the specified distri-ition, passengers will not necessarily incur the same exit delay ne on exiting the aircraft in subsequent simulations. For this ason, it is necessary to repeat a simulation several times in order generate a distribution of results. Furthermore, for each repeat mulation it is possible to impose a different passenger seating ocation. This too will result in the generation of slightly fferent evacuation times. For the relatively small standard narios (see Section 3) with exit separations between 60ft and 0ft each case was repeated 100 times in order to generate a ge of values. Sensitivity analysis revealed that the average of simulations was not significantly different from the average of) simulation runs. The number of simulation repetitions was refore reduced to ten for the remaining cases in order to limit computational load.

) The scenarios described

investigate the impact of exit separation on evacuation efficiency define an aircraft test section that represents a 'typical' section of de-body aircraft located between two pairs of main deck Type-A (see Fig. 1). The study is limited to scenarios in which half the ided exits are made available for the evacuation. This situation is consistent with FAR regulations for full-scale evacuation certification demonstrations[14], which state;

"Not more than 50 percent of the emergency exits in the sides of the fuselage of an airplane that meets all of the requirements applicable to the required emergency exits for that airplane may be used for the demonstration."[14]

In the current investigation only the central section is considered. In this way we limit the passenger flow into each exit to be made up of two components: the flow from the aisle closest to the exit and the cross aisle flow. This represents the simplest possible combination to occur in a wide body aircraft. Indeed sections of this type may be found on current wide body aircraft. If seating sections were available either side of the exit this would result in more complex three way merging flows of passengers at the exits. This situation is also of interest and is the subject of a later study. A total of 220 passenger seats are located between the two pairs of exits. This is the maximum number of passengers, under FAR, that can be accommodated when two pairs of Type-A exits are provided.

The base-case model will simulate a regulatory compliant cabin section. The door to door distance in the base-case, measured from the centre of each door, is 18·1 metres or 59ft 4 inches. This conforms to FAR 25·807.(f)(4) and is therefore regulatory compliant. Extended cabin sections will be constructed and various scenarios simulated. Finally, an alternative seating arrangement is considered.

3.1 Base-case cabin section geometry

The geometry comprises 220 forward facing passenger seats. Each seat has a pitch of 80 centimetres (31·5"). Four Type-A exits are positioned at each corner of the cabin and are labelled R1, R2, L1 and L2. Each row of seating is arranged from left to right as follows: three seats, an aisle, four seats, an aisle, and three seats. Each row of seating contains 10 seats. There are 22 rows of seating in the cabin section. Each Type-A exit is linked to a clear space vestibule area. The vestibule area is of sufficient size to allow six passengers to pack into it with another two passengers in the main aisle space adjoining the vestibule. A small cross-aisle joins the two main aisles and forward vestibule areas. The initial row of seating has direct access to the forward vestibule and cross aisle. The cross-aisle is sufficiently deep to allow a single passenger to stand in the aisle and sufficiently wide to allow a total of four passengers to be accommodated between the main aisles. A similar cross-aisle and vestibule area exists at the rear of the cabin section.

Simulation case	Door-to-door distance	Available exits
S1 base-case	59ft 5in (18·1 metres)	R1 + R2
S2	86ft 11in (26·5 metres)	R1 + R2
S3	114ft 6in (34·9 metres)	R1 + R2
S4	142ft 1in (43·3 metres)	R1 + R2
S5	169ft 7in (51·7 metres)	R1 + R2
S6	197ft 2in (60·1 metres)	R1 + R2
S7	224ft 8in (68·5 metres)	R1 + R2
S8	25ft 4in (76·9 metres)	R1 + R2
S9	279ft 10in (85·3 metres)	R1 + R2
S10	307ft 5in (93·7 metres)	R1 + R2
S11	335ft (102·1 metres)	R1 + R2
S12	362ft 6in (110·5 metres)	R1 + R2
S13	390ft 2in (118·9 metres)	R1 + R2

Table 1
Exit separations and exit availability studied in the S scenarios

Simulation case	Door-to-door distance	Available exits
A1 base-case	59ft 5in (18·1 metres)	R1 + L1
A3	114ft 6in (34·9 metres)	R1 + L1
A4	142ft 1in (43·3 metres)	R1 + L1
A5	169ft 7in (51·7 metres)	R1 + L1
A6	197ft 2in (60·1 metres)	R1 + L1
A7	224ft 8in (68·5 metres)	R1 + L1
A9	279ft 10in (85·3 metres)	R1 + L1
A11	335ft (102·1 metres)	R1 + L1
A13	390ft 2in (118·9 metres)	R1 + L1

Table 2
Exit separations and exit availability studied in the A scenarios

3.2 The generation of longitudinally stretched cabin sections

This study investigates the impact of extending the base-case cabin section beyond the limit of FAR 25.807.(f).(4). Extending the longitudinal door to door distance will create stretched cabin sections. Within airEXODUS cabin space is discretised into nodes. Each node represents an amount of space within the enclosure. Only one passenger may occupy a node at any one time. The size and number of the nodes that comprise a space determine the maximum density that may be achieved for a given amount of spaces.

To enable a direct comparison between all of the airEXODUS models it is necessary to preserve the maximum passenger packing densities within all of the stretched cabin sections. As the cabin is stretched, additional aisle nodes are added in such a manner as to maintain the maximum passenger packing density within the aisles.

As this is a theoretical exercise, some of the exit separations will be increased beyond limits that may be considered practical. This is done in order to derive a theoretical understanding of the relationship between exit separation and evacuation efficiency. In the S (standard) series of scenarios a total of 13 exit separations will be considered (see Table 1) ranging from the base-case of 59ft 5in (18·1m) to 390ft 2in (118·9m).

3.3 Exit availability

FAR regulations for full-scale evacuation certification demonstrations[12] require that not more that 50% of the available exits from an aircraft may be operable. Without exception full-scale certification trials have met this criterion by disabling one exit from each exit pair. In this study, the FAR exit availability criterion will be adhered to, resulting in one of the exits in each exit pair being disabled. In the S scenario series the R1 and R2 exits will be made available (see Table 1).

An alternative and more challenging exit configuration is to have both exits from an exit pair inoperable. This case, referred to as the A scenario series, will also be examined by disabling the L2 and R2 exits. This configuration is also compliant with the certification testing criterion related to exit availability. In addition, analysis of real accident data derived from the AASK (air accident statistical knowledge) database[15,16] suggests that in real accidents, exit configurations in which both exits within a pair are available are more common then single exits.

In the A (alternative exit availability) series of scenarios a total of nine exits will be considered (see Table 2) ranging from the base-case of 59ft 5in (18·1m) to 390ft 2in (118·9m). With the exception of exit availability, all other model parameters are identical to those in the first set of cases.

3.4 Alternative seating arrangement

The cases outlined thus far describe a cabin section that has seating rows arranged in the 3-4-3 configuration. An alternative seating arrangement often found in wide body aircraft consists of the 2-4-2 configuration. Examining this seating configuration will determine if critical exit separation is sensitive to seating configuration. The model is essentially the same as that described in Section 3.1 with 220 seats located within the cabin section. However, the seating arrangement is staggered, as there are 27 rows of window seats and 28 rows of aisle seats. The vestibule areas and exit characteristics are identical to the standard cases (see Fig. 2). The typical certification configuration of available exits will be utilised, i.e. one exit operable from each exit pair.

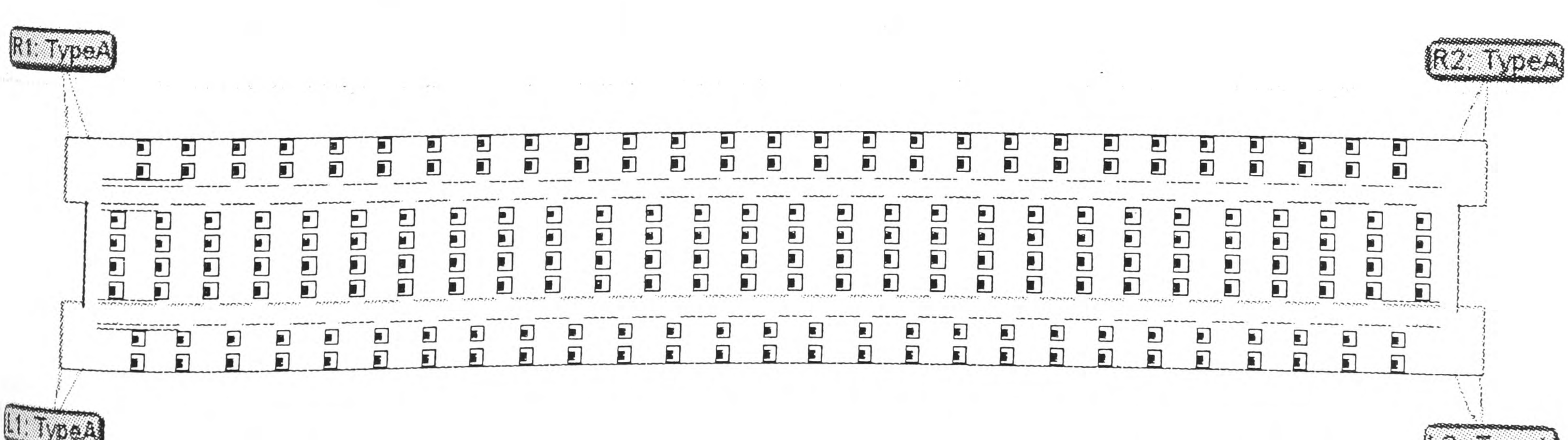


Figure 2. The AS1 (base-case) geometry for the alternative seating arrangement.

Simulation case	Door to door distance	Available exits
AS1 base-case		
AS3		
AS5		
AS7	224ft 8in (68·5 metres)	R1 + R2
AS9	279ft 10in (85·3 metres)	R1 + R2
AS11	335ft (102·1 metres)	R1 + R2
AS13	390ft 2in (118·9 metres)	R1 + R2

Table 3
Exit separations and exit availability studied in the AS scenarios

In the AS (alternative seating) series of scenarios a total of seven exit separations will be considered (see Table 3) ranging from the base-case of 59ft 5in (18·1m) to 390ft 2in (118·9m).

With the exception of seating arrangement, all other model parameters will be identical to those in the first set of cases.

3.5 Passenger behaviour

While airEXODUS has the ability to represent 'extreme' passenger behaviour of the type reported in actual aviation accidents(15,16), such as seat jumping, this type of behaviour is not included in these simulations. All the cases considered here are run under certification type evacuation conditions involving:

(i) Half the total number of aircraft exits;
(ii) Assertive cabin crew located at each Type-A exit;
(iii) Orderly pax behaviour of the type found in certification evacuations; and
(iv) Each exit being made ready in a representative time derived from past relevant certification tests.

However, unlike the behaviour found in certification trials passengers will head for their nearest serviceable exit. This type of passenger behaviour is similar to that found in actual accidents(15-16). This behavioural regime should achieve an optimal distribution of passenger to the exits. In these cases nearest exit use is analogous to an efficient certification trial.

Furthermore, as the exit separation increases, the seat pitch will increase creating a sizeable amount of space between the seats. In the more extreme exit separations it may become possible for passengers to spill into the gaps between the seats and thus overtake slower moving passengers in the aisle. In order to maintain consistency between the various cases, this type of behaviour is not permitted. Passengers are constrained to move only within the aisle spaces. In addition, passengers within the seat rows will not be able to use the additional seat pitch space to their advantage when making their way into the aisle.

3.6 Population specification

Two types of population were created for these simulations. The first set, referred to in the simulations as 'mixed ability', comply with the FAR requirements for certification testing(14). The second population, referred to as 'uniform ability' possesses identical movement capabilities.

Passengers defined in airEXODUS are created using the 90-second population function available in the software. This function generates the required numbers of passengers according to the specified mix (in terms of age and gender) as set out in FAR(14). In airEXODUS, simply specifying the age and gender of each passenger is sufficient. Each person has 21 defining attributes, each of which must be assigned a value. The population tools in airEXODUS allow

Group	Attribute	Min	Max
Males 18-50	Drive	10·0	15·00
	Walk (ms^{-1})	0·5	0·60
	Fast Walk (ms^{-1})	1·0	1·2
	Response Time (s)	0·0	5·0
Males 50-60	Drive	6·0	12·0
	Walk (ms^{-1})	0·35	0·55
	Fast Walk (ms^{-1})	0·70	1·10
	Response Time (s)	4·00	7·00
Females 18-50	Drive	5·00	13·00
	Walk (ms^{-1})	0·45	0·60
	Fast Walk (ms^{-1})	0·90	1·20
	Response Time (s)	0·00	6·00
Females 50-60	Drive	5·00	8·00
	Walk (ms^{-1})	0·25	0·45
	Fast Walk (ms^{-1})	0·50	0·90
	Response Time (s)	5·00	8·00

Table 4
Core attribute ranges for the 90-second populations used in airEXODUS simulations

a range for each attribute to be specified, so that when a person is created, each attribute is assigned a random value between the limits set. The 90-second population consists of four population groups, the core parameters for these groups are distributed as indicated in Table 4. The 'mixed ability' population simply represents a random selection of the 90-second population.

The majority of the attributes assigned to the 'uniform ability' population are essentially identical to the mixed ability population. The only attributes that are different are the fast walk and walk parameters. Both these parameters were uniformly set to the average of the fast walk parameter, i.e. 1·0ms^{-1}.

4.0 Mathematical measures of evacuation performance

In order to assist in the interpretation of data generated by these simulations it is useful to devise a mathematical measure of evacuation performance. Simplistically, the personal evacuation time for a passenger ($T_{evacuate}$) can be broken down into the following components: a pre-movement delay ($T_{pre\text{-}movement}$), the time spent by the passenger actually moving to the exit ($T_{movement}$), the time spent by the passenger in all forms of congestion ($T_{congestion}$) and the passenger's exit delay time (T_{EDT}). The relationship between these factors is described in Equation 1

$$T_{evacuate} = T_{movement} + T_{congestion} + T_{pre\text{-}movement} + T_{EDT} \qquad \ldots (1)$$

where:

$$T_{movement} = D/V \qquad \ldots (2)$$

D = distance travelled by the passenger
V = average travel speed of the passenger

An optimal evacuation time for any given passenger can be achieved if the passenger is able to constantly move towards an exit at their maximum travel speed. To achieve this a passenger must not suffer any delays, such as those arising from congestion or conflicts with other passengers. Essentially a passenger's optimal evacuation time ($T_{optimal}$) is comprised of: a small delay as the passenger responds to the call to evacuate, the time that it takes a passenger to move to an exit and a small delay as the passenger traverses the exit.

$$T_{optimal} = T_{movement} + T_{EDT} + T_{pre\text{-}movement} \quad \ldots (3)$$

$T_{optimal}$ can be approximated from the occupant parameters that are generated during a simulation. The distance travelled by each passenger (from their seat to the exit) can be readily determined by the distance attribute in airEXODUS and is divided by the passengers fast walk airEXODUS parameter yielding $T_{movement}$. The average *TEDT* parameter for each passenger can be determined from the distribution of passenger exit delay times used in airEXODUS and $T_{pre\text{-}movement}$ can be determined from the response time assigned by airEXODUS to each passenger. In this manner a $T_{optimal}$ can be approximated for each passenger.

The actual evacuation times generated by airEXODUS for each passenger (i.e. the PET) will be compared with the $T_{optimal}$ parameter.

Through the subtraction of a passenger's optimal evacuation time from the passenger's actual evacuation time (T_{actual}) we can calculate the amount of time that a passenger spends in congestion ($T_{congestion}$), assuming that all other factors are equal.

$$T_{congestion} = T_{actual} - T_{optimal} \quad \ldots (4)$$

A useful measure of congestion inefficiency can be derived by expressing the amount of congestion that passengers experience during their evacuation as a fraction of the actual time incurred in evacuating. We define this as the *CA* ratio given by Equation 5.

$$CA = T_{congestion} \,/\, T_{actual} \quad \ldots (5)$$

This measure gives the ratio of the amount of time that a passenger spent stationary in congestion to the time actually spent in evacuating. The ratio must yield a value between zero and one, i.e. $0 = CA < 1$. If $CA = 0$ then $T_{congestion} = 0$. Thus if the value of *CA* is zero then the passenger experienced no congestion en route to the exit. If $CA = 0{\cdot}5$, this implies that 50% of the passengers evacuation time was wasted in congestion. It is apparent that *CA* will always be less than one, as the length of time a passenger spent in congestion can never exceed their total evacuation time.

As the cabin section is stretched, passengers will spend proportionally more time moving to an exit as opposed to waiting in a queue at the exit. We could therefore expect *CA* to decrease as the cabin section is stretched. Furthermore if we stretch a cabin section to a suitably large size we could expect the congestion to essentially disappear or more realistically to reduce to a negligible amount, in which case the measure *CA* would approach zero.

The parameter *CA* can be determined for each passenger in an evacuation. $T_{congestion}$ can be determined from the airEXODUS parameter CWT for each passenger. The T_{actual} can be determined from the airEXODUS parameter PET for each passenger.

An average value for *CA* for the entire passenger population can be determined. This is done by summing all of the passenger's individual *CA* values for a simulation and dividing by the total number of passengers as shown in Equation (6).

$$CA_{average} = \frac{\sum_{i=1 \text{ to } P} CA_i}{P} \quad \ldots (6)$$

P = total number of pax

5.0 RESULTS AND DISCUSSION

5.1 Initial results and discussion

In this section we describe and discuss the results of the S1 (standard base-case), S2 (standard stretched 82'), S3 (standard stretched 114') and S4 (standard stretched 142') cases in detail. All of the cases considered in the initial results and discussion section have been

	TET (s)	Average CWT(s)	Average Distance(m	Average PET(s)
Minimum	63·0	21·4	8·5	35·8
Maximum	73·4	25·4	8·7	39·9
Average	67·3	22·9	8·6	37·4

Table 5
Results for scenario S1

		TET(s)	Average CWT(s)	Average Distance(m)	Average PET(s)
(S2)	Minimum	63·7	18·9	10·5	35·4
86' exit	Maximum	76·6	23·3	10·7	40·0
separation	Average	67·6	20·9	10·6	37·5
(S3)	Minimum	63·0	17·4	12·5	36·2
114' exit	Maximum	72·9	21·1	12·7	39·7
separation	Average	67·0	18·9	12·6	37·5
(S4)	Minimum	63·0	15·2	14·5	35·7
142' exit	Maximum	71·3	18·8	14·7	39·3
separation	Average	66·7	16·9	14·6	37·6

Table 6
Summary of evacuation statistics for scenarios S2, S3 and S4

repeated 100 times with the passenger seating location randomised in each run. Statistical results are presented in the form of minimum, maximum and the average result from all 100 repeats for each scenario. Where appropriate just an average value is shown. In all of these cases the mixed ability population is used.

5.1.1 The standard base-case

The S1 case is regulatory compliant and is used to establish a set of base-line results for the proposed cabin section.

It can be seen in Table 5 that the average time required to evacuate the cabin section (i.e. TET) was 67·3 seconds. There is a relatively large degree of variability (10·4 seconds) in the TET values generated, with times ranging from 63·0 seconds to 73·4 seconds. Each passenger spent on average 22·9 seconds stationary in congested areas or queues (i.e. CWT). The average distance travelled by passengers to reach an exit (i.e. distance) was 8·6 metres. Perhaps of greater interest to individual passengers than the TET is the average personal evacuation time (i.e. PET). The average time required by an individual occupant to evacuate the cabin section was 37·4 seconds.

As intended, passengers used their nearest exits, with 110 passengers utilising each exit. It can be seen that in all of the simulations, evacuation of the cabin section was achieved in less than 90 seconds, thus satisfying the 90-second certification requirement.

5.1.2 Standard stretched cases S2, S3 and S4

The following section examines the simulation results for the standard S2-S4 cabin sections utilising exits R1 and R2. The results are contrasted with the base-case scenario described in the previous section.

Closer examination of Table 6 suggests that there is a greater degree of variability in the evacuation times for the S2 case than for the other cases. Inspection of the individual evacuation times in the S2 case reveals two abnormally high evacuation times (76·4 and 74·1 seconds). These high evacuation times are responsible for the

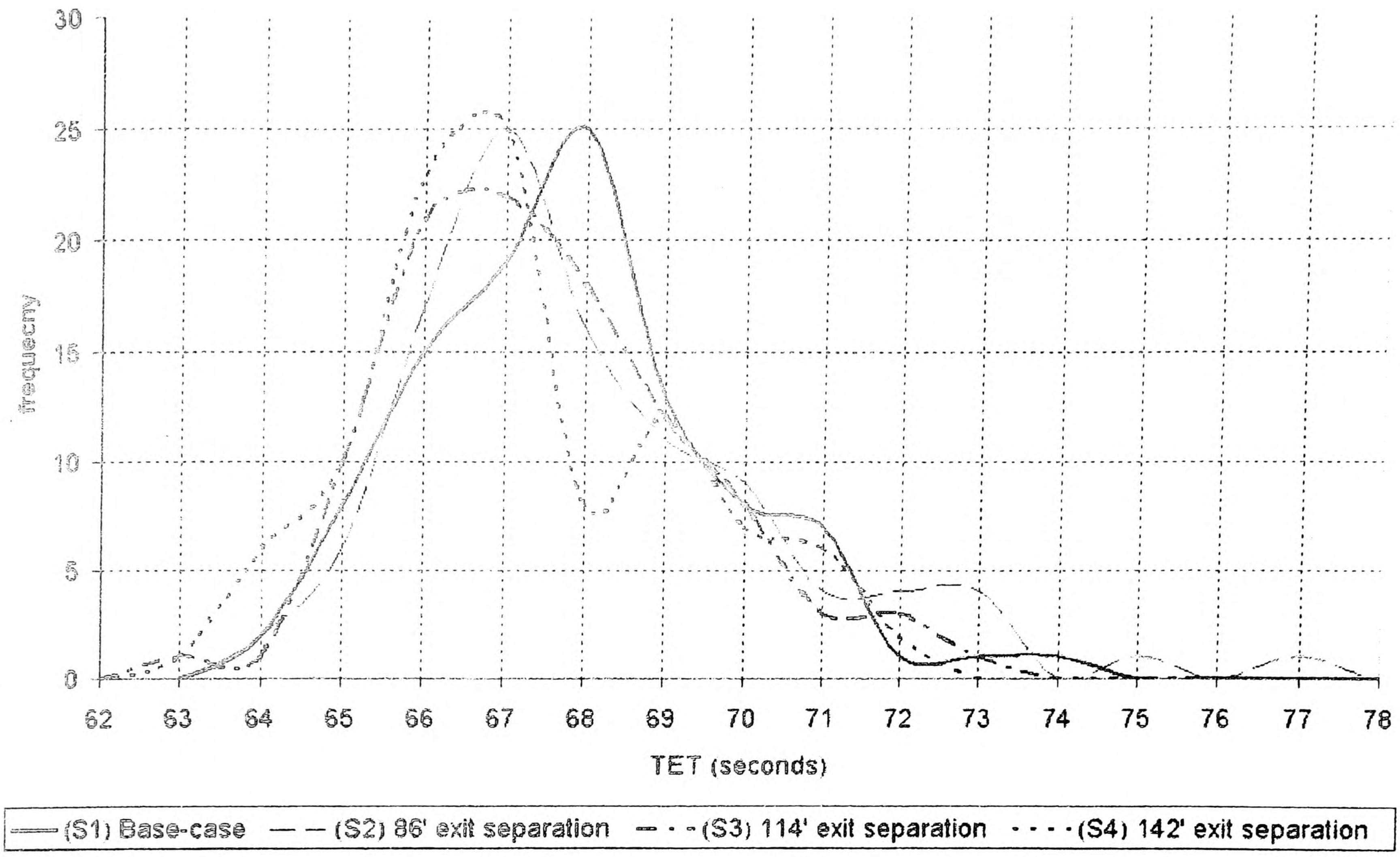


Figure 3. Frequency distribution of TET for the S1, S2, S3 and S4 cases.

increased range. Examining the animations generated for these two cases reveals that the long evacuation times are caused by a large group of less mobile elderly passengers being seated in distant locations from the exits. As these passengers are less mobile it takes them a significant length of time to reach the vestibule area. Upon reaching the vestibule they vie with each other for access to the exit thus incurring conflict delays and further increasing their evacuation times. This incident occurred as a result of the randomisation of passenger starting location and was not due to the differences in aircraft geometries. Similar population randomisation did not occur in the other cases.

In contrast to the total evacuation time, it can be seen in Table 6 that as the size of the stretch increases, the average amount of time passengers waste in congestion decreases from 22·9 seconds in the base-case to 16·9 seconds in S4. This suggests that the level of congestion is decreasing as the length of the cabin section is increased. This point is illustrated in Fig. 4(a), which plots the average CWT for each simulation run. Similarly, we note from Table 6 that as the size of the stretch increases, the average distance travelled by the passengers increases from 8·6m in the base-case to 14·6m in S4. This is graphically represented in Fig. 4(b).

As the distance between the exits increases, on average passengers must travel further to evacuate. While this results in an increase in movement time ($T_{movement}$), this is compensated for by an equivalent reduction in the levels of congestion encountered (CWT in airEXODUS), resulting in both the personal evacuation time (PET in airEXODUS) (see Table 6) and the total evacuation time (see Fig. 4(c)) remaining unchanged.

In these cases, stretching the cabin section has no significant impact on the overall evacuation time (i.e. TET) and, more importantly, from an individual passengers perspective the average time required for a passenger to evacuate (i.e. PET).

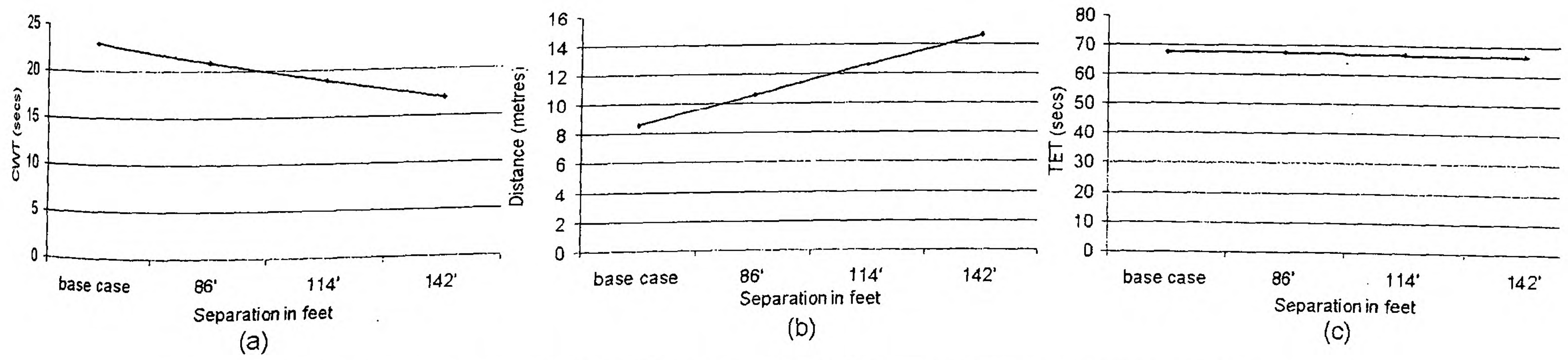


Figure 4. Results from scenarios S1 to S4 showing (a) the average CWT, (b) the average travel distance and (c) total evacuation time as a function of exit separation.

	S1 – Base-case	S2 – 86'	S3 – 114'	S4 – 142'
Seated pax	113	109	50	38

Table 7
The average number of passengers situated in seat rows after ten seconds of simulation

5.2 Passenger behaviour

Through examining the animations generated by a particular simulation, airEXODUS allows us to develop qualitative understanding of the dynamics involved in the evacuation. The following discussion will examine the rationale behind the results presented thus far, and offer some insight into the underlying behaviours that generate the results.

By stretching the cabin section we create more space in the aisles. This means that passengers should be able to clear their seats more rapidly as the cabin is progressively stretched, reducing the time wasted in congestion at the aisle-seat row interface. This type of congestion we refer to as 'seat row congestion'. The average number of passengers situated in seat rows after ten seconds is shown in Table 7 for the various cabin stretches. As the cabin section is stretched the number of passengers situated in seat rows after ten seconds is reduced. Increasing the ease by which passengers may exit seat rows and take a position in the aisle is desirable as this reduces the number of space conflicts thereby reducing the amount of time wasted in seat row congestion and hence this portion of the CWT.

However, the dominant areas of congestion in these cases occur adjacent to the exits. Congestion forms at the exit as large numbers of passengers arrive at the exit vestibule within a relatively short period of time. As each exit has a finite flow rate capability, passengers are forced to wait. Thus congestion develops adjacent to the exit and stretches into the aisles. As it is the size and associated flow-rate of the exit that precipitates the formation of this congestion, we refer to this type of congestion as 'exit congestion' and the associated queues as 'exit queues'.

Exit queues are formed as a result of the limited flow capacity of exits. However, once generated the queue's dynamics influence the operational flow rate of the exit. Exit performance relies upon the exit queues providing a steady supply of passengers to the exits. If the queues operate in an inefficient manner then so do the exits. If the queues only sporadically supply passengers to a vestibule area, an exit may become idle as the exit is starved of passengers.

Queue dynamics are also affected by less mobile passengers. In these simulations, severe mobility impaired passengers (i.e. those classified as disabled) are not considered however, elderly passengers with reduced mobility akin to those used in certification trials are included. In the S3 and S4 cases it was noted that the queues tended to divide into many smaller 'sub-queues'. These sub-queues formed as slower moving (less mobile) passengers delayed faster moving passengers. A queue of mixed ability passengers thus became segregated into multiple smaller 'sub-queues'.

Less mobile passengers tended to become the head of sub-queues. This is a result of less mobile passengers being unable to keep pace with the person immediately in front of them causing a small gap to develop between themselves and the passenger in front. Since the less mobile passenger is moving slowly, more mobile passengers, positioned behind them in the queue, are forced to adjust their movement speed to that of the less mobile passenger, thus the less mobile passenger becomes the head of a sub-queue. As there may be several less mobile passengers in a queue several sub-queues may be formed. The amount of time that a passenger wastes through being held up by less mobile passengers is referred to as 'sub-queue congestion' which contributes to $T_{congestion}$ and the overall CWT in airEXODUS. An example of sub-queues can be seen in Fig. 5.

The presence of gaps in queues resulting from sub-queue formation can have a negative impact on exit flow rates and hence evacuation efficiency by creating a deficit in passenger supply to the vestibule area. Consider the situation in which one exit from each exit pair is operable. In this case each vestibule area has two aisles supplying passengers. If one aisle experiences a period of zero passenger flow, the other aisle can compensate and provide passengers to the exit. If however we consider the exit availability configuration where both exits from an exit pair are operable then each exit will generally be supplied by a single aisle. Under these conditions, it is possible that gaps resulting from sub-queue formation could contribute to periods of reduced passenger exit flow resulting in a reduction in evacuation efficiency.

The formation of sub-queues is considered to be a real effect that will influence the evacuation efficiency as described above. In order to better understand the impact of exit separation on evacuation efficiency the propensity to form sub-queues has been removed in some cases. This is achieved through the inclusion of a set of simulations using the so-called 'uniform ability' population described in Section 3.6.

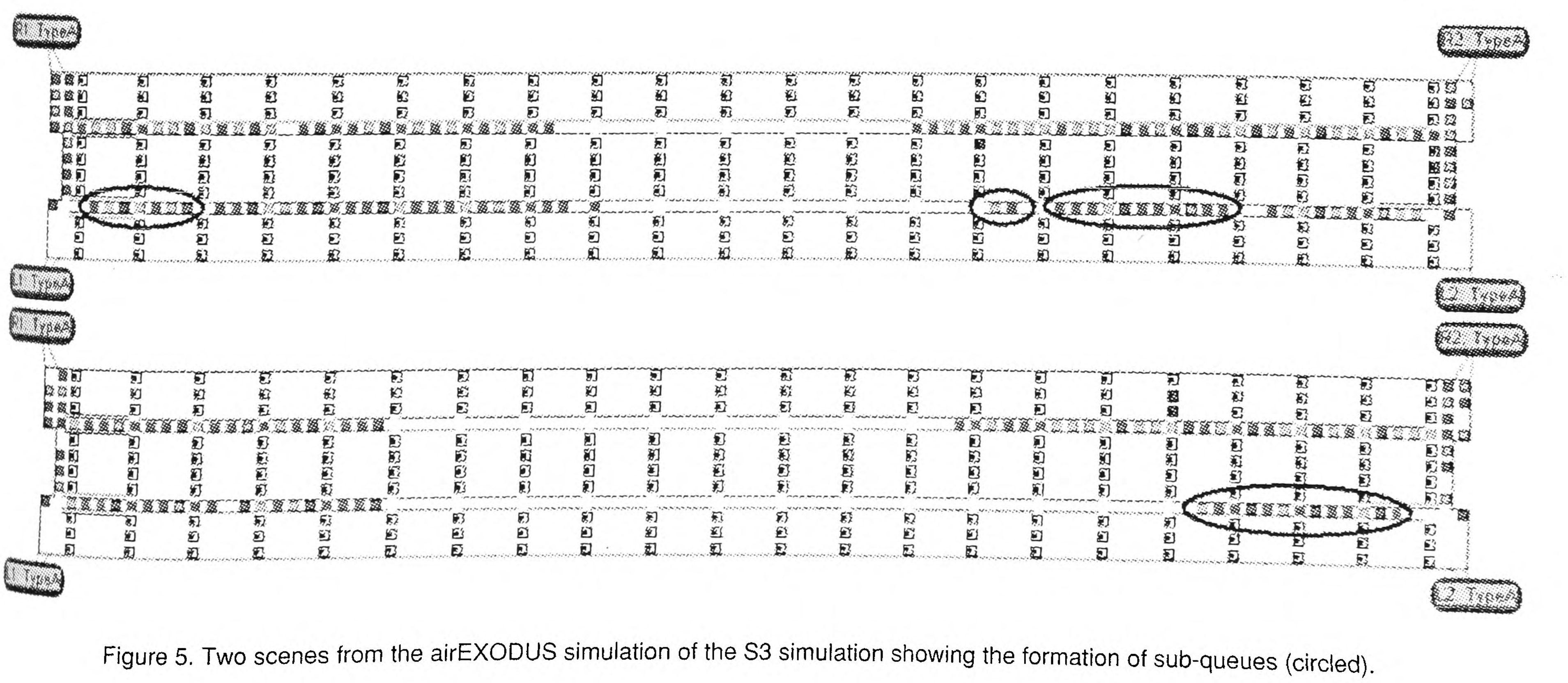
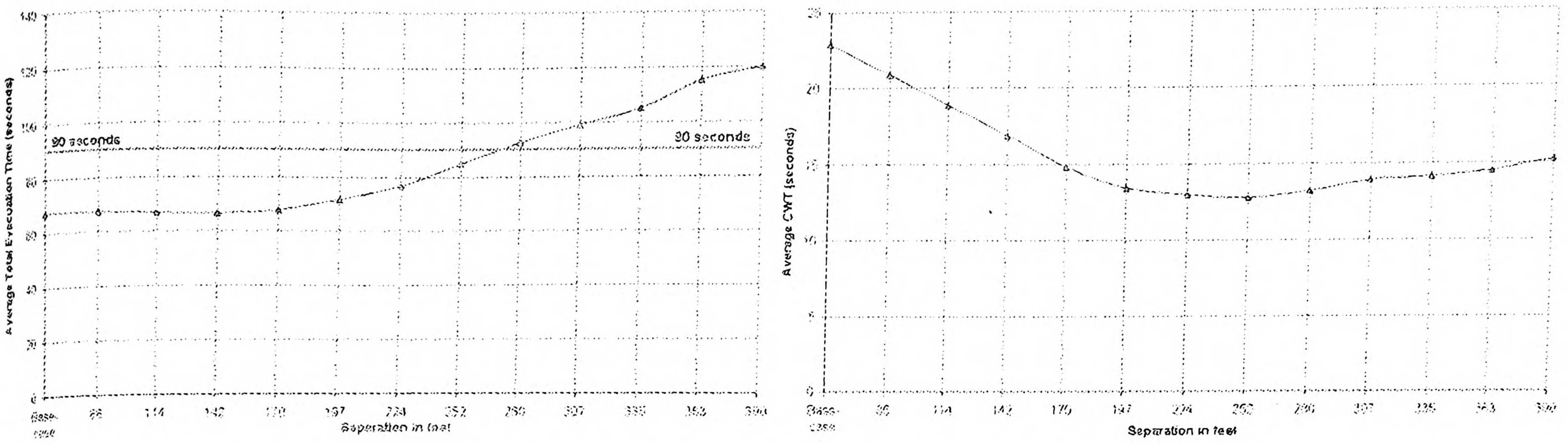
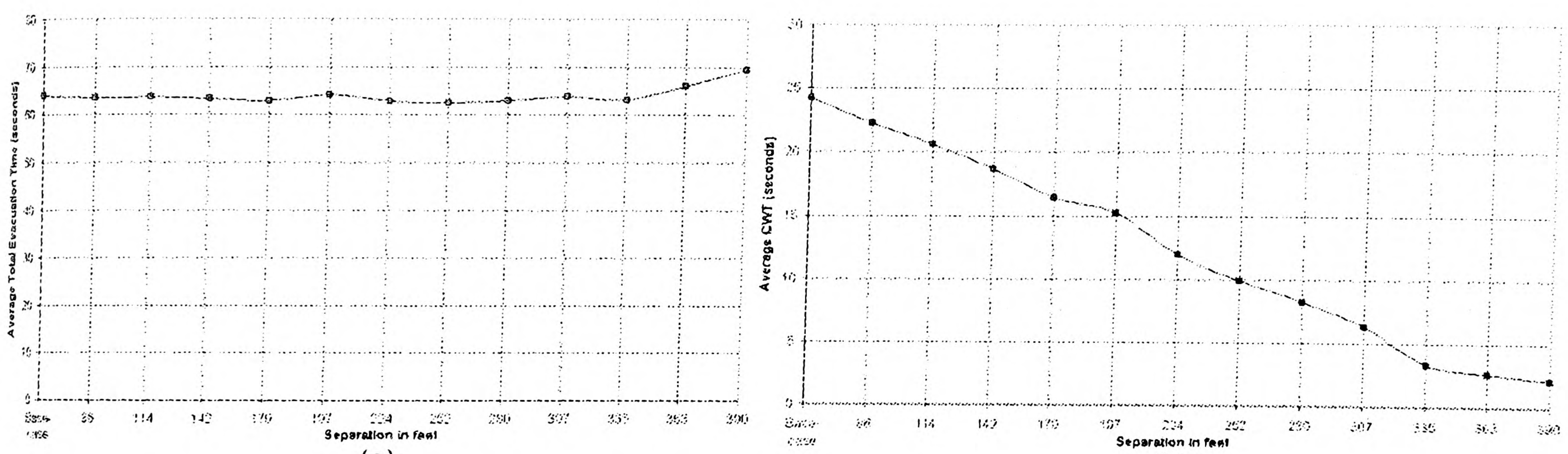


Figure 5. Two scenes from the airEXODUS simulation of the S3 simulation showing the formation of sub-queues (circled).



(a) (b)

Figure 6. Results of the S scenarios with mixed ability populations. (a) TET as a function of exit separation and (b) CWT as a function of exit separation.



(a) (b)

Figure 7. Results of the S scenarios with uniform ability populations. (a) TET as a function of exit separation, (b) CWT as a function of separation.

2.1 *Standard stretched cases S1-S13*

laving studied in detail several 'small stretch' cases, we now onsider the evacuation of the larger stretch cases. The results and iscussion of S5–S13 (standard cases: 170', 197', 224', 252', 280', 07', 335', 363' and 390') are presented. Due to the large amount of nalysis involved in the calculation of the *CA* mathematical measure, is calculation is based on data from five simulation runs. More stanard airEXODUS result data such as TET, CWT, OPS, distance and ET are based on ten iterations of each simulation case. Analysis of e results from ten and 100 simulations suggest that there are no gnificant differences between the averages.

The average TET and CWT for each case are plotted in Fig. 6(a) r all of the S scenarios with mixed ability populations. It can be en that the TET remains at approximately 67 seconds for the first e cases. Once the separation exceeds 170ft the TET starts to rise the cabin section is further stretched.

Examination of the CWT plotted in Fig. 6(b), reveals that for dest cabin stretches, the CWT begins to decrease as the stretch reases. However, it begins to plateau at a value of approximately seconds after an exit separation of 170ft. After a separation of 2ft the average CWT begins to gradually increase. Counter intuely, the congestion does not continue to decrease despite the in section becoming increasingly stretched. This is thought to be to sub-queue formation.

The impact of sub-queue formation can be examined by repeating simulations using the uniform ability population. Depicted in Fig. 7(a) is the average TET and Fig. 7(b) the average CWT for each of the standard cases with the uniform ability population.

Examination of the average CWT for the uniform ability cases (Fig. 7(b)) reveals that the CWT steadily decreases from a value of 24·2 seconds in the base-case to 3·3 seconds at approximately 335ft. After this point, CWT continues to decrease, but at a reduced rate, reaching 2·1 seconds at an exit separation of 390ft. This suggests that the average CWT has decreased essentially to zero. The small residual congestion is most likely the result of differences in passenger pre-movement delays and conflicts arising from differences in passenger exit hesitation times. Consistent with this, we find that the average TET (Fig. 7 (a)) remains roughly uniform at 63 seconds until a separation of 335ft, after which the TET begins to increase. The constant value for the TET is dependent on the uniform movement rate assigned to the passengers.

The evacuation dynamics responsible for the curves seen in Fig. 6 and Fig. 7 can now be explained as follows. With a mixed ability population, as the exit separation is gradually increased from 60ft up to 170ft, the total evacuation time remains essentially unchanged. This is due to the increase in travel distance being off-set by the reduction in exit queue congestion experienced by the passengers as they take longer to reach the exit. As the exit separation increases beyond 170ft, the TET begins to increase. This is due to several factors. Primarily it is the presence of mixed ability passengers who cause sub-queues to form that exert an influence on evacuation efficiency. This causes passengers to experience greater delays resulting

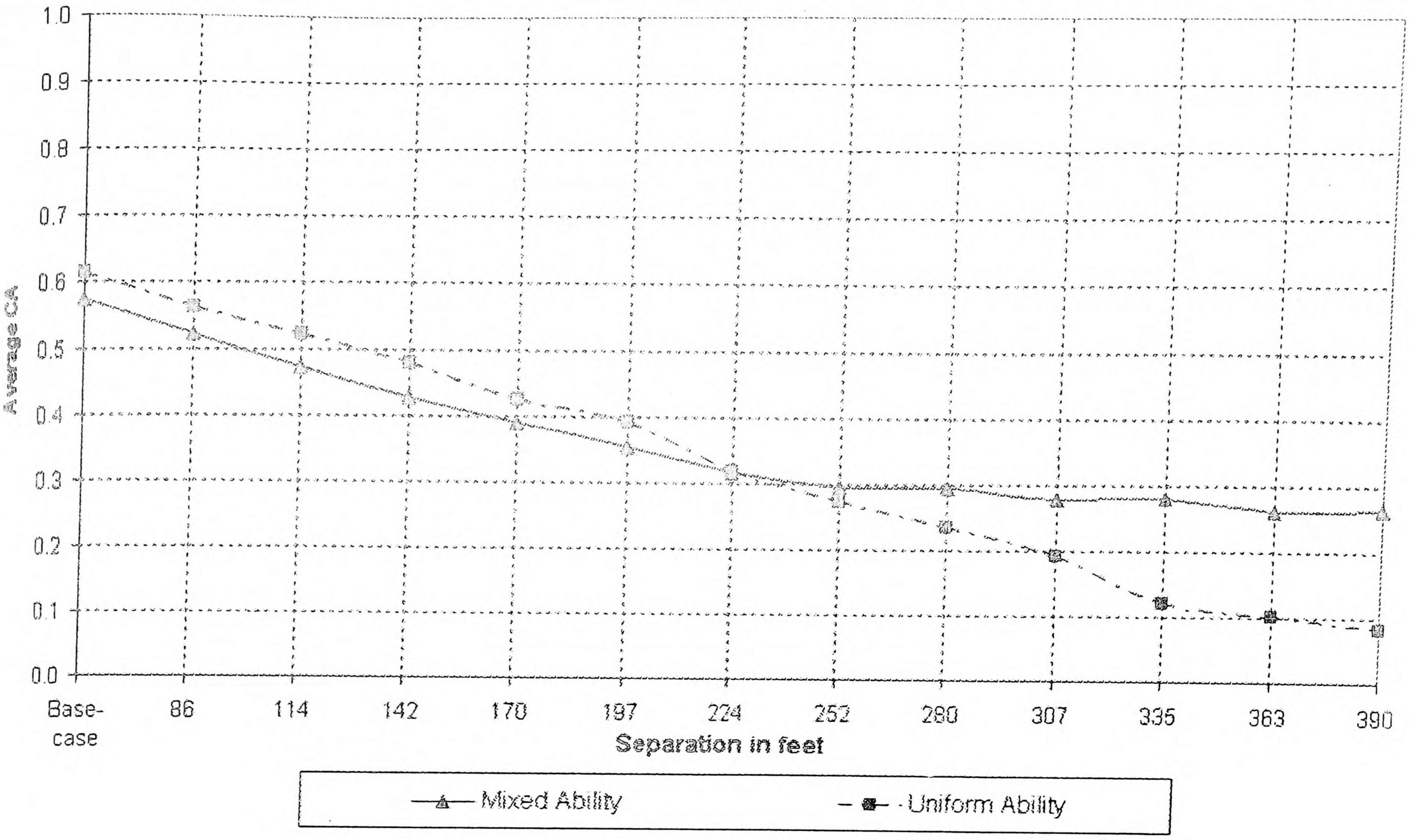


Figure 8. The *CA* measure for the s scenarios as a function of exit separation.

in a gradual increase in CWT and hence TET. In addition — as the stretch continues to increase beyond 335 feet — the increased distance travelled by the passengers is no longer compensated for by the decrease in exit congestion. When passengers of uniform ability are used, the sub-queue congestion is essentially removed and we find that the TET does not begin to increase until the exit separation exceeds 335 feet. This indicates that exit congestion has been eliminated in the uniform cases at a separation of 335ft.

The level of optimality attained in these simulations can be gauged using the average *CA* (see Equation (6)) ratio. Whilst in this paper it is not possible to provide a thorough description of this analysis, it is revealing to examine how the *CA* ratio is affected by increases in exit separation.

The *CA* ratio is plotted against exit separation in Fig. 8. It can be seen that for relatively moderate exit separations of less than 224ft, the mixed ability population's average *CA* steadily decreases from 0·57 at 60ft to 0·39 at 224ft. This indicates that as the exit separation increases, the evacuation becomes more efficient with the average percentage of evacuation time that passenger's waste in congestion decreasing from 57% to 39% of the optimal evacuation time. Over this range of exit separations, the time wasted in congestion is dominated by exit congestion as both the uniform and mixed ability populations display similar values of *CA*. From Fig. 6(a) we note that the TET remains constant up to a separation of 170ft. This indicates that as the exit separation increases, passengers spend increasingly more of their time moving as opposed to waiting in congestion.

At relatively large separations (i.e. those in excess of 224ft) the mixed ability population curve begins to plateau at a value of approximately 0·27, i.e. the average percentage of time that passenger's waste in congestion remains roughly constant at 27% of total evacuation time. However, the uniform ability curve continues to decrease, reaching a value of 0·08 at 390ft. At these exit separations, sub-queue congestion becomes the dominant factor resulting in the uniform ability populations becoming more efficient than the mixed ability populations.

The average PET for a simulation is the average amount of time that each passenger required to evacuate the cabin section. Using the previously proposed definition for a passenger's optimal evacuation time (see Equation (3)) we can calculate each passenger's optimal evacuation time and then determine the average optimal PET for a simulation. Depicted in Fig. 9 is the average PET as determined from airEXODUS for the S series of simulations using mixed and uniform populations as well as the average optimal PET as a function of exit separation.

For the compliant exit separation, we note in Fig. 9 that the average PET for the mixed ability population is 38·1 seconds, for the uniform ability population it is 36·7 seconds while the optimal PET is 13·7 seconds. For exit separations less than 170ft, the PET for the mixed and uniform ability populations remain essentially unchanged as the exit separation is increased while the optimal PET increases uniformly as a direct result of the increased travel distance. Thus increasing the exit separation up to 170ft makes no difference to the average personal evacuation time in the mixed ability cases. For the uniform ability population, the PET remains approximately constant up to an exit separation of 335ft after which it begins to increase.

This suggests that for these configurations and these scenarios an exit separation of 170ft is the 'practical exit separation threshold' that cannot be exceeded without an adverse effect on evacuation times. If a uniform ability population is used, the practical exit separation threshold is increased to 335ft. To understand what contributes to these thresholds it is necessary to consider the generation of congestion within the cabin section.

The difference between the PET for the mixed and uniform ability populations is a direct result of congestion created by sub-queue formation. For exit separations less than 170ft, the small difference between these two constant PET values suggests that sub-queue formation contributes an insignificant amount to the total time wasted in congestion. The difference between the PET for the mixed ability population and the optimal PET is a result of exit congestion, seat row congestion and sub-queue congestion. Up to exit separations of 170ft, the difference between the PET for the mixed ability and the optimal PET decreases as the exit separation increases. This suggests that the exit congestion and seat row congestion is decreasing while the sub-queue congestion remains constant as the exit separation is increasing. The PET (and TET) remains constant over this range of exit separations because the extra travel time incurred by travelling the extra distance is compensated for by reductions in exit and seat congestion.

For exit separations greater than 170ft, the PET for the mixed ability population begins to increase with exit separation. In addition, the difference between the PET for mixed ability populations and the optimal PET becomes almost uniform after a separation of 224ft is exceeded.

In the mixed ability cases it is after 170ft that sub-queue congestion begins to play a more significant role in determining the total time wasted in congestion. This can be seen by examining the differences between the mixed and uniform ability curves and the uniform and optimal curves. While the difference between the mixed and uniform curves is increasing i.e. sub-queue congestion is becoming more significant, the difference between the uniform and optimal curves is decreasing, i.e. exit and seat row congestion is becoming less significant. Thus for the mixed ability population, the increases in both the travel time and the sub-queue congestion are not compensated for by reductions in exit and seat congestion and so the PET begins to increase. For exit separations in excess of 170ft, the sub-queue congestion increases as the exit separation increases because the more mobile passengers are caught behind the less mobile slower moving passengers for significantly longer duration.

At exit separations above 335ft, exit congestion no longer exerts a significant influence and consequently the difference between the uniform ability and optimal curves significantly reduce. In this region, the main contributor to the PET (T_{actual}) is the actual movement or travel time ($T_{movement}$). Thus if sub-queue congestion could be avoided, the practical exit separation threshold could be extended from 170ft to 335ft.

It should be recalled here that in this analysis it is assumed that the maximum permitted number of passengers is situated between the exits. The levels of congestion — exit, seat and subqueue — will be affected by the number of passengers present. Thus, it is expected that the 'practical exit separation threshold' will be affected by the number of passengers situated between the exits. In situations where the number of passengers is significantly reduced, it is expected that the 'practical exit separation threshold' will likewise be reduced.

This leads to the somewhat counter-intuitive conclusion that in situations where the number of passengers is significantly reduced (thereby significantly reducing congestion levels), the 'practical exit separation threshold' will likewise be reduced. This can be demonstrated through a simple example. Consider a situation where only one passenger populated the cabin section and that the exits are open and ready for use prior to the evacuation. As there is only a single passenger, clearly there will be no congestion. Indeed, in this case the TET will simply be a function of the time required to respond, move to and then traverse the exit. Hence the practical exit separation threshold would effectively be zero. In this situation any increase in exit separation would directly result in the passenger having to travel further and hence require more time. This additional travel time can not be compensated for by reduction in queuing time as there is no congestion at the exit. Thus as the passenger load is reduced and hence the level of congestion, the practical exit separation threshold is also expected to reduce.

To summarise, for simulated mixed ability populations evacuating the test cabin section under certification conditions, the optimum exit separation is roughly 170ft. If exit separation is increased above this value, both average PET and TET will

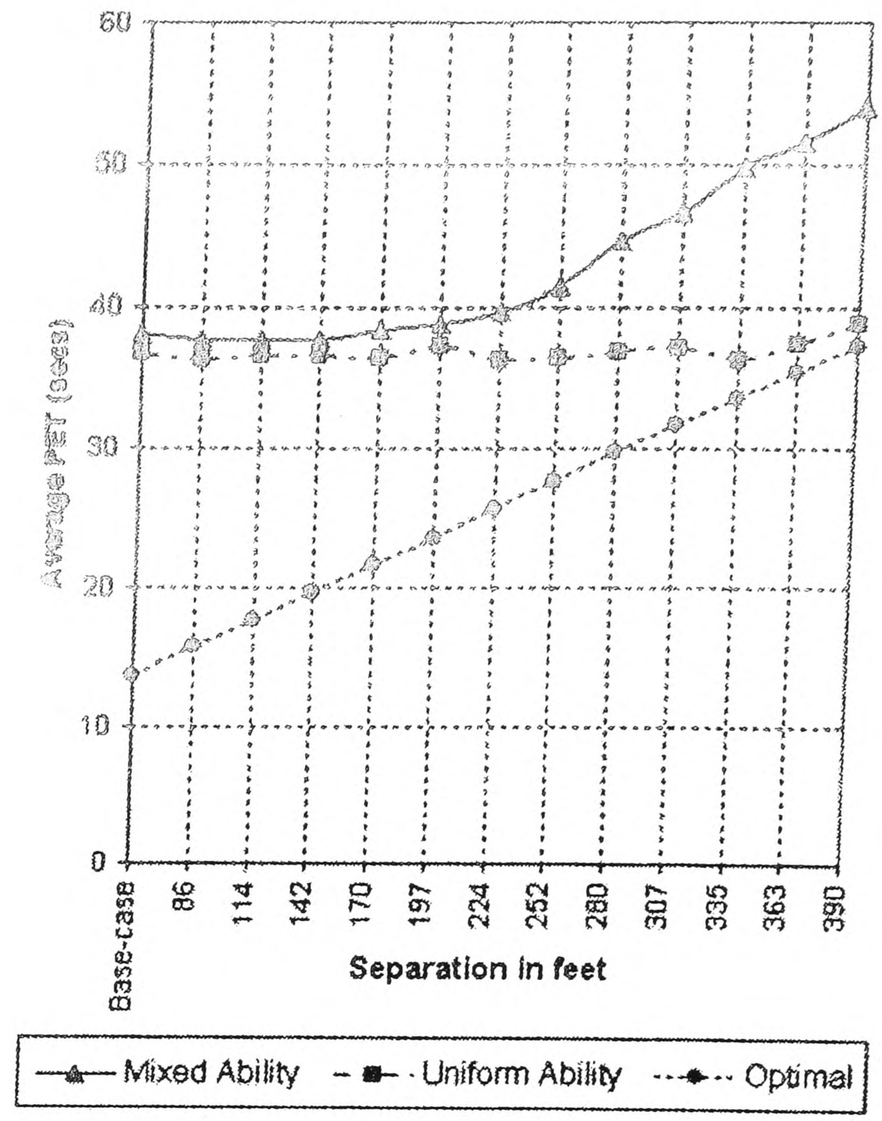


Figure 9. Average PET (seconds) for the standard cases as a function of exit separation (feet).

increase. For exit separations less than this critical value, both the average PET and TET remain constant as the exit separation is increased. This is due to the extra travel time incurred by travelling the additional distance being compensated for by reductions in congestion, in particular exit and seat congestion. For exit separations above this value, sub-queue congestion begins to exert a significant influence on evacuation efficiency. While exit congestion is decreased as the exit separation is increased further, this reduction is compensated for by the increase in sub-queue congestion. With an exit separation of more than 280ft, sub-queue congestion has increased to such a level that the reduction in exit congestion becomes insignificant in comparison. Once the exit separation has exceeded 335ft, exit congestion has effectively ceased to be an issue while sub-queue congestion remains. It is interesting to note that for mixed ability populations, time delays resulting from congestion can never be completely removed.

5.3 Alternative exit availability configurations

All of the scenarios considered thus far are akin to certification conditions in that they have only one operable exit in each exit pair. Here we investigate an alternative exit configuration that maintains the certification requirement of 50% exit availability. In these cases both exits from the forward exit pair will be made available while both exits from the aft exit pair are inoperable.

This arrangement of exits results in two key differences between the standard and alternative cases that will have an impact on evacuation dynamics and hence may influence the practical exit separation threshold. The standard exit configuration employed in certification trials minimises the total travel distance incurred by the passengers. In the test cases examined previously in this paper, it is

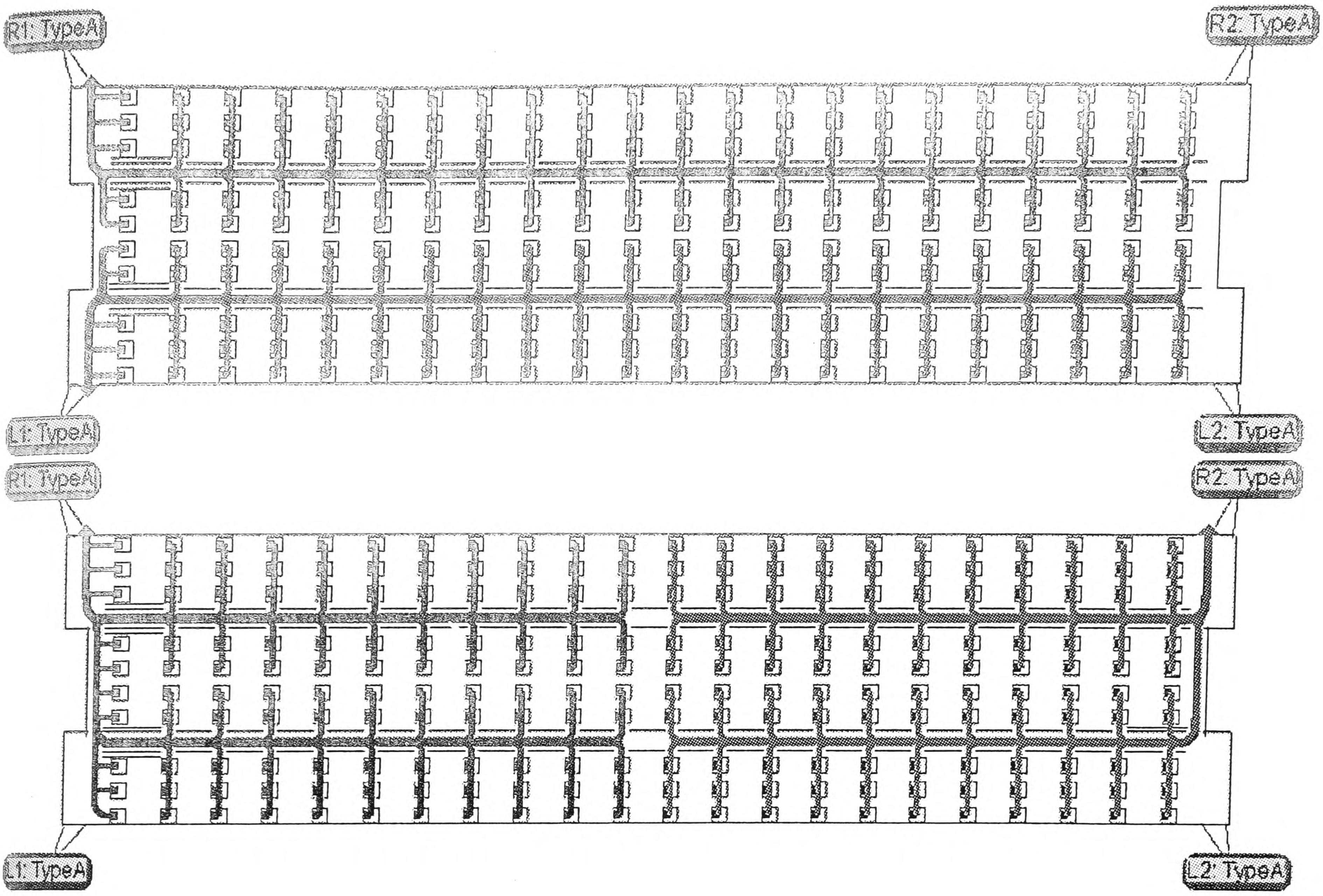


Figure 10. The predicted path of movement for the two exit configurations examined namely, (a) the alternative exit configuration with the aft exit pair inoperable and (b) the standard configuration with one exit from each exit pair inoperable.

apparent that using the certification exit configuration, the maximum travel distance is equivalent to 11 rows of seating (measured to the exit vestibule). However, if both aft exits are inoperable and both front exits are operable, the maximum travel distance is doubled to 22 rows of seating.

The second key difference between the configurations concerns the number of main aisles that supply each exit. The cabin section used in this investigation — being representative of wide-bodied aircraft — possess two main aisles. In this analysis, the aisles are considered to be the only way that the passengers can reach the vestibule area and subsequently exit the aircraft (competitive behaviour resulting in seat climbing is not considered in this analysis). If we consider a configuration of exits where one exit from each exit pair is operable, it is apparent that both aisles can be utilised by the passengers in reaching the vestibule area adjacent to exits. Considering the case where both exits from an exit pair are operable it is apparent that each exit will be serviced by only one aisle - assuming that passengers use their nearest exit (see Fig. 10).

5.3.1 *Alternative configuration of available exits results and discussion*

This section considers the results for cases A1–A13 (alternative cases with exit separations ranging from 60–390') as described in Table 2. Both mixed and uniform ability populations are used in these simulations.

The mixed ability base-case produces an average TET of 92·5 seconds (see Fig. 11(a)). This is significantly higher than the average TET for the standard mixed ability base-case which produced an evacuation time of 67·3 seconds (see Table 5). The average flow rate achieved in the base-case for the A series simulations was 82 passengers/minute while the exits in the S series base-case simulations achieved an average flow rate of 120 passengers/minute. This is a general trend that is seen in all exit separations. It should be noted that each exit in both the A and S simulations used an identical passenger exit hesitation time distribution as described in Section 2.2.

It was observed in the S series simulations that the dual-lane Type-A exits operated with minimal periods of single-lane flow. Furthermore, the exits were constantly supplied with passengers such that there were no noticeable periods when the exit was idle (non-flow). This was due to the vestibule area adjacent to the exit being continuously packed with passengers, due to the steady supply of passengers from the near main aisle and cross-aisle. By comparison the exits in the A series simulations experienced periods of non-flow and single-lane exit flow.

The single-lane flow results from the Type-A exit flow capacity exceeding the flow capacity of the single main aisle that supplied each exit with passengers. The vestibule area adjacent to the exit was therefore not fully packed with passengers resulting in a reduced flow of passengers from the aisle to the exit.

In the A series simulations, the periods of exit non-flow were caused by an uneven supply of passengers. In these cases each exit is

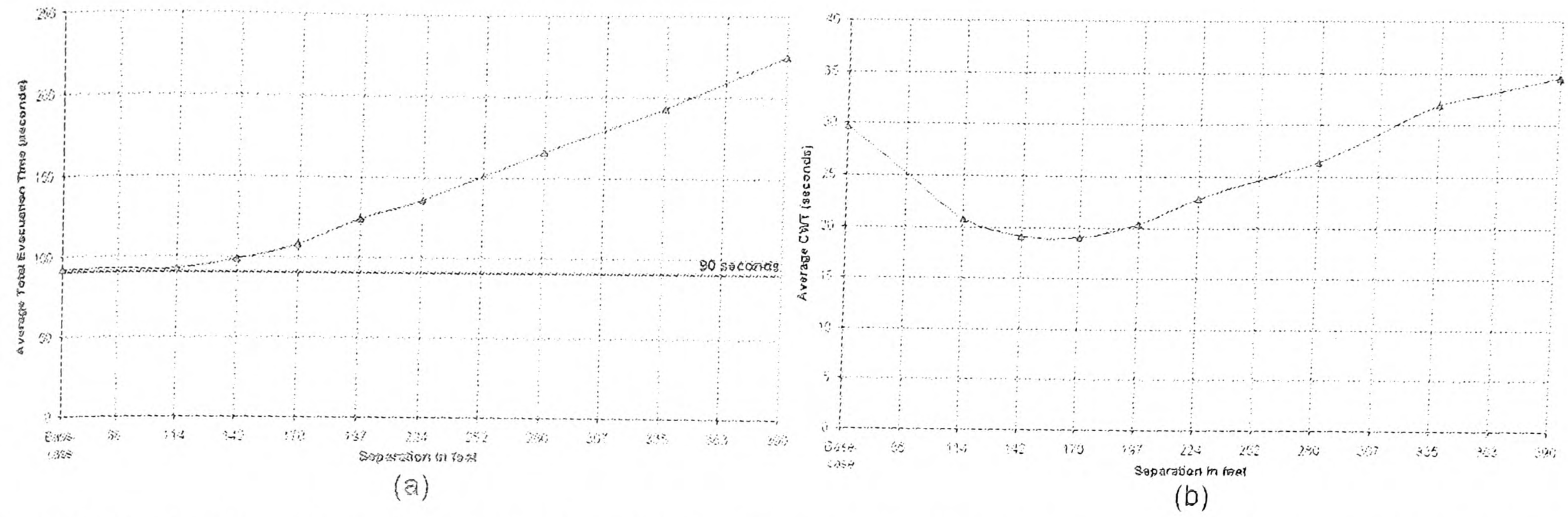


Figure 11. Results of the A scenarios with mixed ability populations. (a) TET as a function of exit separation and (b) CWT as a function of exit separation.

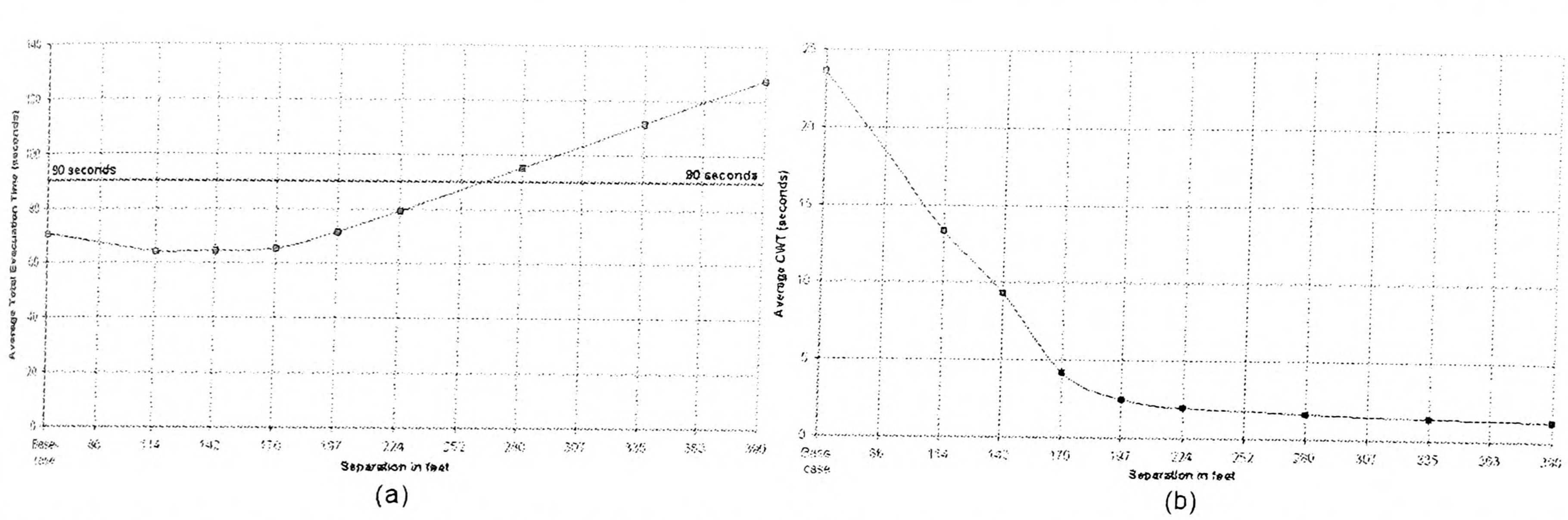


Figure 12. Results of the A scenarios with uniform ability populations. (a) TET as a function of exit separation and (b) CWT as a function of exit separation.

pplied by only a single main aisle and so is susceptible to disruptions in passenger aisle flow. Should the continuous flow of passengers from the aisle be disrupted, by for example sub-queue congeson (which generates gaps between passengers in the queues), then e exit will experience a similar gap in the flow of passengers, thus ading to a period of non-flow. Unlike the S scenarios, there is no cond aisle in the A scenarios to compensate for a momentary eak-up of the continuous flow of passengers.

Thus the increase in the average evacuation times for the A series se-case is related to the poor performance of the exits in these pulations compared to the S simulations. This decrease in exit rformance is a direct result of the decreased level of service to the its, which is caused by the reduction in number of aisles that pply each exit.

The average TET and CWT for each case are plotted in Figure 11 all of the A scenarios with mixed ability populations. It can be n that the TET remains at approximately 93 seconds up to an exit aration of approximately 114ft. Once the separation exceeds 114 the TET starts to rise as the cabin section is further stretched. increase becomes more pronounced (indicated by a higher dient) after a separation of 170ft.

xamination of the CWT plotted in Fig. 11(b), reveals that for est cabin stretches, the CWT begins to decrease from its value of econds as the cabin is stretched. However, it begins to plateau at lue of approximately 19 seconds after an exit separation of 142 After a separation of 170ft the average CWT begins to gradu- increase.

e results from the A series simulations with mixed ability population show identical trends to those observed in the S series (see Fig. (6)) however, the critical exit separations are greatly reduced. The practical exit separation threshold for the mixed ability population in the A scenarios appears to be 114ft compared to 170ft in the S scenarios. As found in the standard configurations, sub-queue formation is believed to cause the increase in CWT as exit separation is increased.

As with the S series simulations, the impact of sub-queue formation can be examined by repeating the simulations using the uniform ability population. Depicted in Fig. 12(a) is the average TET and Fig. 12(b) the average CWT for each of the alternative configuration with uniform ability population.

Examination of the average CWT for the uniform ability cases (Fig. 12(b)) reveals that the CWT steadily decreases from a value of 23·6 seconds in the base-case to 4·2 seconds at approximately 170ft. After this point, CWT continues to decrease, but at a reduced rate, reaching 1·3 seconds at an exit separation of 390ft. The small residual congestion is most likely the result of differences in passenger pre-movement delays and conflicts arising from differences in passenger exit hesitation times. Consistent with this we find that the average TET (Fig. 12(a)) remains roughly uniform at 64 seconds until a separation of 170ft, after which the TET begins to increase. The constant value for the TET is dependent on the uniform movement rate assigned to the passengers.

As with the mixed ability cases, the results from the A series simulations with uniform ability population show identical trends to those observed in the S series (see Fig. 7). However, the critical exit separations are greatly reduced. It is apparent that the levels of

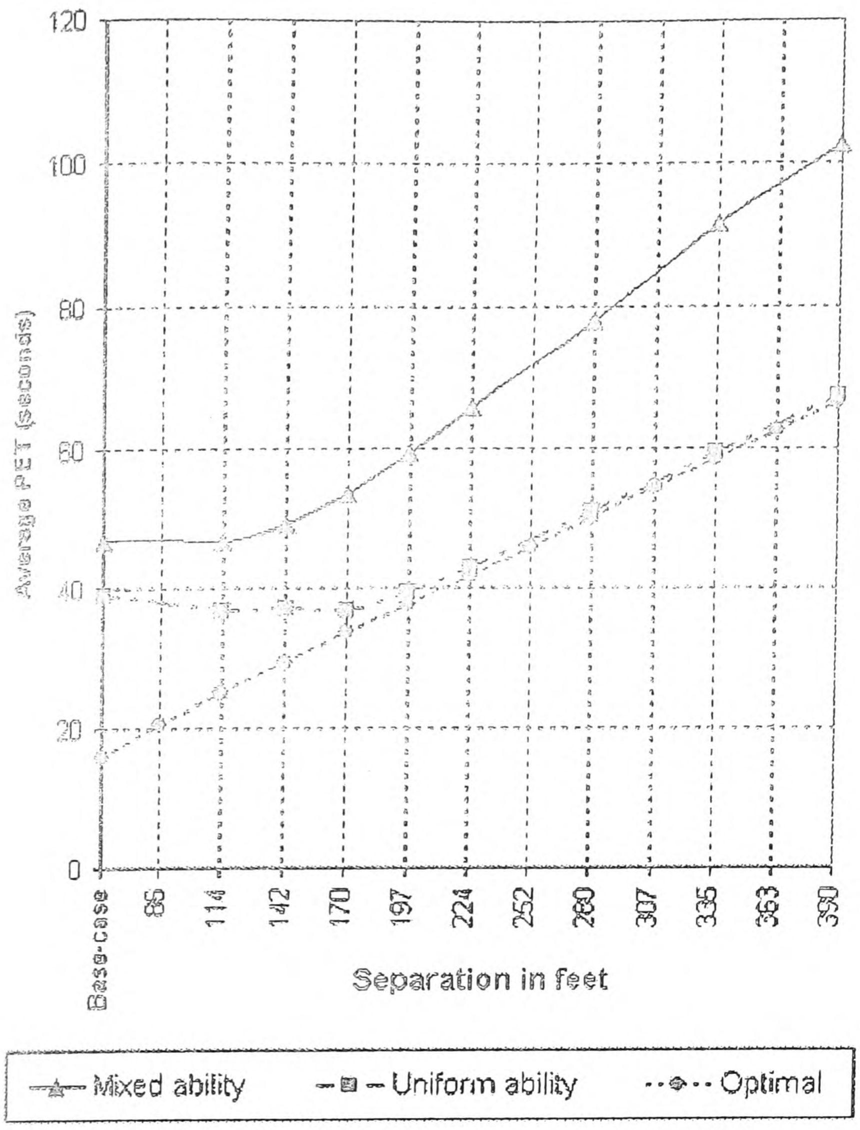


Figure 13. Average PET (seconds) for the alternative cases as a function of exit separation (feet).

congestion as measured by the CWT for mixed ability populations are greater in the S series cases than those in the A series cases. However, when considering the uniform ability cases, the situation is reversed. If sub-queue congestion could be removed, the practical exit separation threshold in the A series scenarios could be increased to 170ft (compared with 335ft in the standard cases).

Depicted in Fig. 13 is the average PET as determined from airEXODUS for the A series of simulations using mixed and uniform populations as well as the A series average optimal PET as a function of exit separation.

For the alternative exit separation, we note that the average PET for the mixed ability population is 47 seconds (compared with 38·1 seconds in the standard case), for the uniform ability population it is 39 seconds (compared with 36·7 seconds in the standard case) while the optimal PET is 16 seconds (compared with 13·7 seconds in the standard case). For exit separations less than 114ft, the PET for the mixed and uniform ability populations remain essentially unchanged as the exit separation is increased while the optimal PET increases uniformly as a direct result of the increased travel distance. Thus increasing the exit separation up to 114ft makes no difference to the average personal evacuation time. For the uniform ability population, the PET remains constant up to an exit separation of 170 feet after which it begins to increase.

As noted earlier, the overall results and trends are identical to those found in the standard cases. The significant difference being that the 'practical exit separation threshold' has decreased from 170ft to 114 feet for the mixed ability population and 335ft to 170ft for the uniform ability population.

The main reason for these differences concerns the extra travel distance that must be travelled for a given exit separation in the alternative configuration compared with the standard configuration (see Fig. 14). This essentially makes an exit separation (i.e. cabin section length) in the alternative configuration equivalent to a larger exit separation in the standard case. Thus increasing the average travel

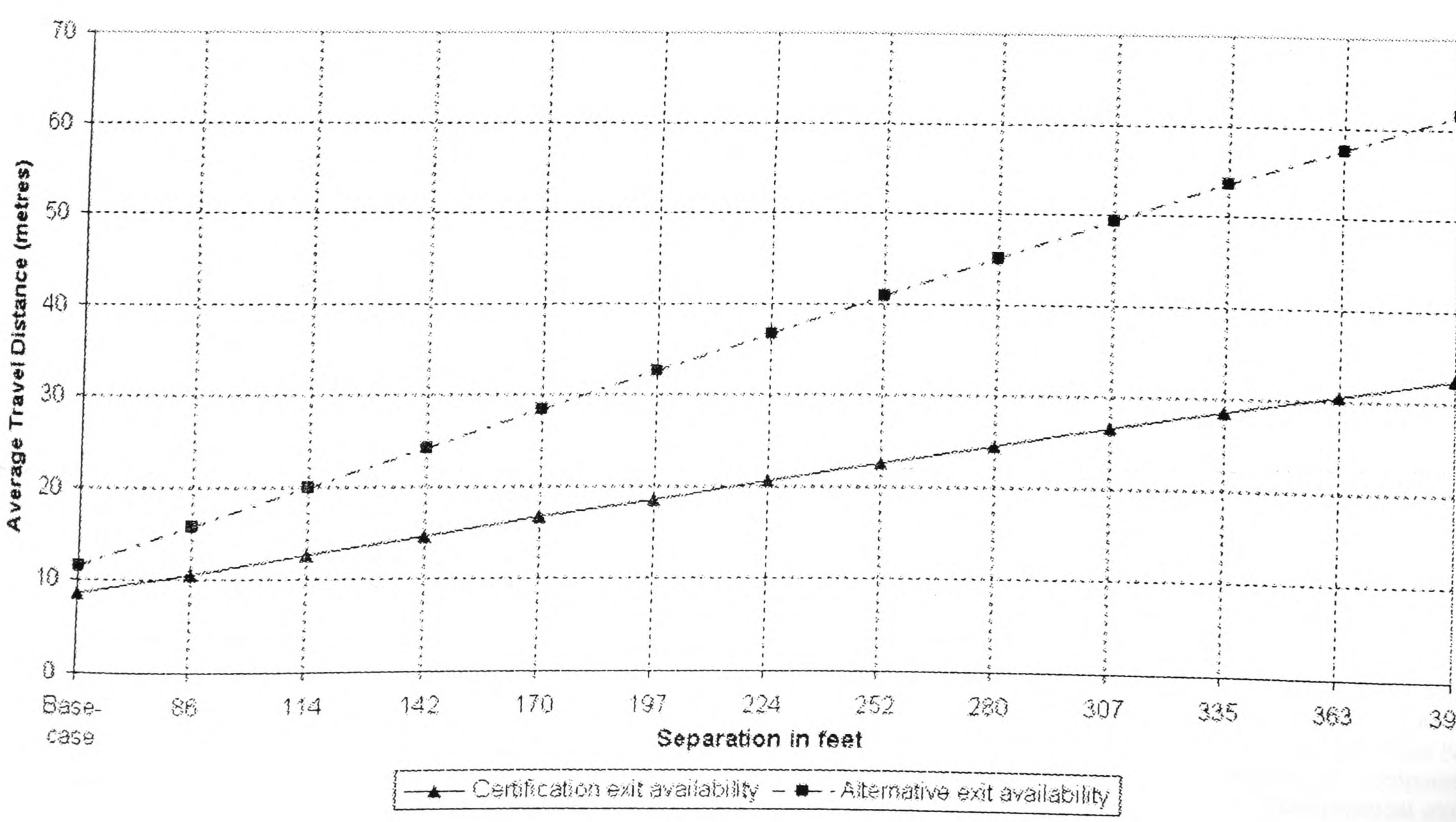


Figure 14. The average distance (metres) travelled by passengers in the standard and alternative exit availability cases.

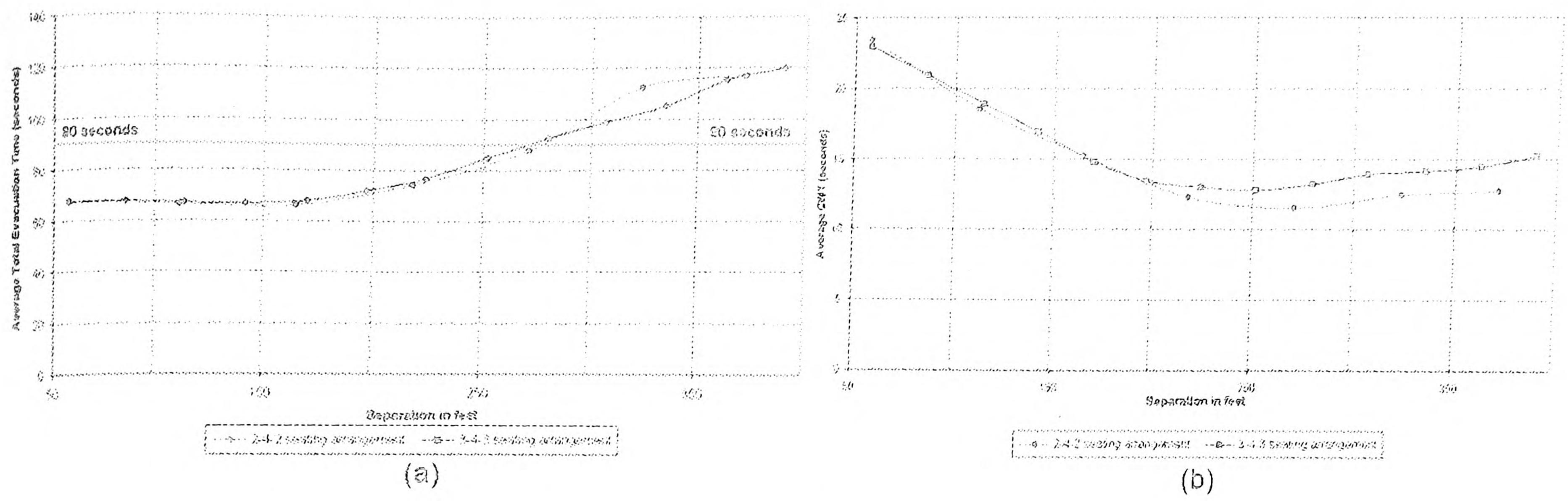


Figure 15. Results of the AS scenarios with mixed ability populations. (a) TET as a function of exit separation and (b) CWT as a function of separation. Results for the AS (2-4-2) scenarios are shown as dashed lines while the S (3-4-3) scenarios are shown as solid lines.

distance has the effect of reducing the practical exit separation threshold. It was also noted that the flow rate achieved by the exits in the alternative configuration was considerably less than that achieved in the standard configuration. A reduction in flow rate at the exit will tend to increase the exit congestion and thus tends to compensate for the additional travel distance. Thus, it is expected that decreasing the exit flow capability has the effect of increasing the practical exit separation threshold. In this case, the trend in decreasing the exit separation threshold was more significant than the trend in increasing it and so a net decrease resulted.

This implies that exit flow rate capability is an important factor in letermining maximum exit separation. If an exit has a reduced exit low rate capability, the 'practical exit separation threshold' is xpected to be increased. This is a factor that is ignored in the urrent regulations. Thus, if the Type-A exit in these simulations vere replaced with a Type-I exit, it is likely that the practical exit eparation threshold for the standard scenarios could be increased to ell above 200ft (assuming the same population size). Finally, the crease in the TET noted in the alternative cases compared to the andard cases is also related to the both these factors.

4 Alternative seating cases results and discussion

e final case to be considered involves an alternative seating rangement. Here we compare a seating configuration of 2-4-2 with 3-4-3 configuration examined in the previous sections. The exit ailability is the same as that used in the standard cases.

.1 *Alternative seating configuration results and discussion*

s section considers the results for cases AS1–AS13 (alternative ting cases with exit separations ranging from 60-390 feet) as cribed in Table 3. Only the mixed ability population is used in se simulations.

The TET and CWT for the standard (3-4-3) and alternative (2-4-2) ting arrangements are superimposed as a function of exit separa- in Fig. 15. It is clear from these results that the overall trends are similar. The results suggest that the 'practical exit separation shold' for the AS and S cases are approximately the same.

appears that an alternative seating arrangement does not signifi- ly affect the evacuation dynamics, presuming that the cabin ions are similar in terms of size, availability and type of escape ities, i.e. aisles, vestibule areas, and that the seating is even distributed throughout the available space. In both arrangements of seating the 'practical exit separation threshold' is positioned at a separation of approximately 170 feet.

6.0 CONCLUSIONS

This work has highlighted that under certification conditions, amongst other factors, three types of congestion, namely 'exit congestion', 'seat congestion' and 'sub-queue congestion' exert a significant influence on evacuation efficiency. All three of these factors are strongly influenced by the exit separation and exit flow dynamics.

A main finding of this work is that for the population and cabin section investigated and under certification conditions, exit separations of 60 to 170ft will result in approximately uniform averages of total evacuation times and personal evacuation times. This suggests that with this cabin section under these conditions, an exit separation of 170ft is the 'practical exit separation threshold' for Type-A exits that cannot be exceeded without an adverse effect on evacuation times.

For stretches of the cabin section between these limits whilst under the same conditions, the additional travel time incurred by passengers travelling the extra distance is compensated for by reductions in congestion, in particular exit and seat congestion. For stretches that are above 170ft, exit congestion, while decreasing remains a significant factor and sub-queue congestion begins to exert a significant influence on evacuation efficiency. The additional travel time incurred by passengers in travelling the extra distance is effectively still compensated for by the non-zero exit congestion. However, sub-queue congestion begins to delay passengers resulting in an increase in evacuation times. Once the exit separation has exceeded 335ft, exit congestion has effectively ceased to be an issue while sub-queue congestion remains.

Another significant finding concerns the influence of exit availability on the 'practical exit separation threshold'. If certification conditions are maintained with the exception that both exits from an exit pair are available while no exits from the alternative exit pair are available, the 'practical exit separation threshold' (which in this case relates to the length of the cabin section) for this cabin section is decreased to 114ft. This is due to the additional distance that must be travelled for a given exit separation in this configuration compared with the previous configuration. This suggests that the practical exit separation threshold is strongly dependent on which combination of 50% of the exits are selected i.e. the nature of the scenario.

Furthermore, it was noted that having two exits in an exit pair available results in a decreased exit flow rate compared with the previous configuration. It is suggested that if an exit has a reduced exit flow rate capability, the practical exit separation threshold is increased, thus exit flow rate capability is an important factor in determining maximum exit separation. Another finding concerned the passenger seating arrangements. It was noted that seating arrangements of 2-4-2 and 3-4-3 produced almost identical average evacuation and congestion times. Hence, the practical exit separation threshold was not found to be sensitive to seating arrangement.

The intuitive feeling that exit separation is an important parameter in determining aircraft evacuation efficiency has been substantiated. However, this work has revealed that there is a complex relationship between the two. Indeed, other factors such as exit flow rate and exit availability have been shown to exert a strong influence on the critical exit separations. By implication, the number of passengers located between the two exits is also an important parameter. While not explicitly considered in this paper, it is expected that if the number of passengers between the exits were greatly reduced, thereby reducing the levels of congestion, this would have the effect of greatly reducing the practical exit separation threshold. If correct, this has major implications as it suggests that the 'worst case scenario' from an exit separation view occurs not when the maximum number of passengers are considered but when fewer passengers are considered.

These results suggest it is not advisable to mandate a maximum exit separation without taking into consideration exit type, exit availability, occupancy load and aircraft configuration. This has implications when determining maximum allowable exit separations for wide and narrow body aircraft. It is also relevant when considering the maximum allowable separation between different exit types on a given aircraft configuration.

This work also suggests that from the view of evacuation efficiency under certification conditions, exit separations greater than 60 feet are not expected to influence the evacuation time. This is not to say that in designing a 'safe' aircraft it is acceptable to have exit separations greater than 60ft. Other factors apart from evacuation time under the current FAR 25.803 evacuation scenario should be considered when determining maximum exit separations. For instance, passenger disability, the presence of fire and smoke, the orientation of the aircraft, changes in passenger behaviour associated with these hazards, reduced passenger numbers in addition to the parameters already identified are important parameters that need to be taken into consideration. To correctly take all these factors into consideration when designing and approving new aircraft types requires a performance based regulatory environment that takes a holistic view of safety rather than the existing prescriptive environment.

Finally, these findings are based on a numerical assessment derived from the application of an aircraft evacuation model. The derived conclusions are therefore dependent on the parameters used in the model and the veracity of the model. Some differences in the conclusions are to be expected if different parameters such as passenger travel speeds, exit geometry, etc are considered however, the overall trends are expected to be maintained. Needless to say, the conclusions can be substantiated through targeted experimental trials.

7.0 FUTURE WORK

In the current investigation only a central cabin section was considered. In this way the passenger flow into each exit was made up of two components, the flow from the aisle closest to the exit and the cross aisle flow. If seating sections were available either side of the exit this would result in more complex three way merging flows of passengers at the exits. This type of configuration should be investigated. The level of occupancy directly affects the level of exit congestion and consequently the positioning of the practical exit separation thresholds. An analysis of reduced occupancy is therefore essential. Cases involving fires may constitute the worst case scenario for a stretched cabin section. In addition, passengers with movement disabilities may also be included. These cases should therefore be examined. Finally, the analysis should be repeated for narrow-bodied aircraft.

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The use of evacuation modelling techniques in the design of very large transport aircraft and blended wing body aircraft

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ABSTRACT

Very Large Transport Aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed. Other more radical concepts such as blended wing body (BWB) design, involving one or two decks with possibly four or more aisles offer even greater challenges. Can the largest exits currently available cope with passenger flow arising from four or five aisles? Do we need to consider new concepts in exit design? Should the main aisles be made wider to accommodate more passengers? In this paper we demonstrate how computer based evacuation models can be used to investigate these issues through examination of staircase evacuation procedures for VLTA and aisle/exit configuration for BWB cabin layouts.

1.0 INTRODUCTION

Very large transport aircraft (VLTA) pose considerable challenges to designers, operators and certification authorities. VLTA designs currently being considered are capable of carrying 800+ passengers with interiors consisting of two aisles and two full-length passenger decks. Other more radical concepts consist of a blended wing body (BWB) design, involving one or two decks with possibly four or more aisles. The drive for increased efficiency, passenger capacity and aircraft size is balanced by the need to maintain, and if possible, improve current safety standards. One of the highest safety priorities for aircraft designers and regulators alike concerns the evacuation efficiency of aircraft design. Questions concerning seating arrangement, nature and design of recreational space, the number, design and location of internal staircases, the number, location and type of exits, the number of cabin crew required and the nature of the cabin crew emergency procedures are just some of the issues that need to be addressed.

The massive increase in passenger capacity and aircraft size being suggested also challenge some of our preconceptions in equipment design and crew emergency procedures. For instance, in order to efficiently complete an evacuation, will it be necessary to extend emergency procedures to the marshalling of those passengers evacuated to the ground? Imagine a situation with 800 passengers on the ground, possibly on one side of the aircraft. What impact will they have on fire fighting and rescue operations? Who should take responsibility for the grounded passengers? Should evacuation procedures be developed that allow passengers to travel between decks before exiting the aircraft? How will crew communicate effectively to control such an evacuation on a single deck and between decks? Will the proximity of multiple emergency slides have a detrimental effect on evacuation efficiency and safety? Can exits be safely spaced further apart than the current arbitrary 60ft limit(1)? What impact will this have on evacuation times and survivability?

If BWB aircraft become a reality, should designs incorporate continuous solid cabin partitions along the length of the aircraft? Should these cabins have cross aisles linking each cabin section? Will it be sufficient to simply have exits in the forward and aft sections of the aircraft? Can the largest exits currently available cope with passenger flow arising from four or five main aisles? Do we need to consider new concepts in exit design, perhaps introducing three or four lane exits? How efficient can a three or four lane exit be in evacuating passengers? Should the main aisles be made wider to accommodate more passengers? How much time is actually required for safe egress from a BWB aircraft? Does the 90-seconds concept(2) have any relevance to VLTA and BWB aircraft?

Quite apart from questions of emergency evacuation, issues concerning the appropriateness of VLTA and BWB designs in allowing the rapid and efficient movement of passengers during boarding and disembarkation are an additional essential design consideration. Furthermore, these requirements may potentially conflict with the requirements for emergency egress. Ultimately, the practical limits on passenger capacity are not based on technological constraints concerned with aircraft aerodynamics but on the ability to evacuate the entire complement of passengers within agreed safety limits.

While there are currently no VLTA flying, the Airbus 380 has been labelled a VLTA by some. The A380, while physically the largest passenger aircraft currently planned does not represent a massive increase in passenger capacity, at least for its standard configuration. The standard passenger seating capacity of the A380 is reported to be 550 passengers in a three class configuration(3) however, significantly greater seating capacity options are possible, with

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822 passengers being suggested for the single class configuration[4]. This is compared with the Boeing 747-400 that carries 416 in a three class configuration with a reported maximum of 660 for the single class configuration[4]. Another feature of the A380 is that it has two passenger decks positioned one on top of the other. This in itself is not unusual or novel as the B747 has flown with an upper deck for many years. While it may be debated whether the new Airbus A380 should be classified as a VLTA, the number of passengers that are seated on the upper deck make the A380 different to existing aircraft.

With the upper deck comes the need to evacuate passengers using the upper deck exits and slides. A feature of upper deck exits is that the exit slides are much longer than those of more 'standard' exits. For example, on the B747 the upper deck sill height is 7·8m and on the A380 it is set to be 7·9m above the ground[5]. One assumption concerning the use of high sill height exits is that passengers would hesitate longer at the upper deck exit before they jumped onto the slide compared to lower height main deck exits. While there is very little data concerning the use of upper deck slides under certification evacuation conditions, what data that is available suggests that this is not the case, and that passenger exit hesitation delays while slightly longer are similar to those of more standard exits[6,7]. Clearly, more research in the form of component testing is required to generate the required data.

In addition to higher sill heights, longer exit slides and large numbers of passengers located on upper decks, VLTA double deck aircraft can possess one or more staircases. Again, in itself this is not a new concept as the B747 has flown for many years with a staircase connecting the two decks. While evacuation procedures for VLTA may not require the use of the staircase(s) in order to pass an evacuation certification trial, it is desirable that staircase design be appropriate for evacuation situations. Emergency evacuation scenarios may develop where it is necessary or desirable to evacuate all or some passengers down the stairs and out the main deck exits rather than out the upper deck exits. While less likely, accident situations may also develop where it is necessary to move some passengers to the upper deck and out the upper exits. While this may not be a problem for existing aircraft, the sheer number of passengers located on the upper deck of VLTA configurations makes this an issue worth investigating.

Currently, the FAR 25 aviation regulations (800 series governing evacuation issues) are silent on the issue of staircase design[8]. This omission could lead to the development of sub-optimal conditions during an evacuation should the staircase be needed as a means of escape. As an example, the height of a stair riser and the depth of a stair tread are known to be important factors in determining the ease of use and efficiency of staircase design. Additionally, the requirement for handrails that separate a wide staircase into lanes has long been recognised as essential in building and marine regulations[9,10]. It is recognised that central handrails enable passengers to use the entire width of the staircase during an emergency evacuation as opposed to 'hugging' the walls close to the outer handrails. Handrails are mandatory in building codes as they provide support to occupants and serve as guides for people whose vision may be impaired due to smoke and/or lighting failure[10]. In addition, within building codes it is recognised that to be effective the handrails must be within reach of staircase users[10]. Therefore building codes mandate that handrails must be within 30in of the "natural path of travel"[10]. Onboard marine vessels the requirement for handrails is of even more importance as marine vessels are subject to dynamic and static changes in pitch and roll. Similar situations could develop on aircraft that have crashed and have gear failure.

Aircraft staircase design has been studied in previous research undertaken by the FAA Civil Aerospace Medical Institute (CAMI) in 1978. This involved a series of trials to determine the movement rate of passengers through spiral and straight staircases with and without handrails under various pitch and roll conditions[11]. The staircases that were investigated were very narrow having an effective width of 20in. As such the passengers evacuated in single file and used the handrails extensively. Unfortunately, the staircase width used in these experiments is simply not relevant for staircases that are expected to accommodate two or more passengers simultaneously. While there are no specific rules addressing staircases in the FAR, special conditions were specified for the certification of the B747. These conditions do not specify staircase design constraints but state objectives that should be meet by good staircase design, e.g. stairs must be safe, must work in adverse attitude conditions etc.

Computer based aircraft evacuation models — together with reliable data — have the potential to address all of these issues and provide manufacturers, operators and regulators a means of assessing novel designs, procedures and accident scenarios associated with VLTA and BWB. In a previous publication, the authors demonstrated how aircraft evacuation models could be used to investigate the rationale behind existing prescriptive rules associated with exit separation, the so-called 60ft rule[1]. In this paper we will demonstrate how computer based evacuation models can be used to investigate issues associated with VLTA configuration and crew procedures and how they can contribute to the design of the even more radical BWB cabin layouts.

2.0 THE AIREXODUS MODEL

2.1 EXODUS Overview

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of complex enclosures. Development of the EXODUS concept began in 1989. Today, the family of models consists of building EXODUS[12-15], maritime-EXODUS[16,17] and airEXODUS[1,15,18,19,20,21,22] for the built, maritime and aviation environments respectively.

airEXODUS is designed for applications in the aviation industry including, aircraft design, compliance with 90-second certification requirements, crew training, development of crew procedures, resolution of operational issues and accident investigation. The airEXODUS model and its validation has been described previously[1,15,18-22] and so only the components relevant to this study will be briefly described here.

The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the **PASSENGER, MOVEMENT, BEHAVIOUR, TOXICITY** and **HAZARD** sub-models (see Fig. 1). The software describing these sub-models is rule-based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. These submodels operate on a region

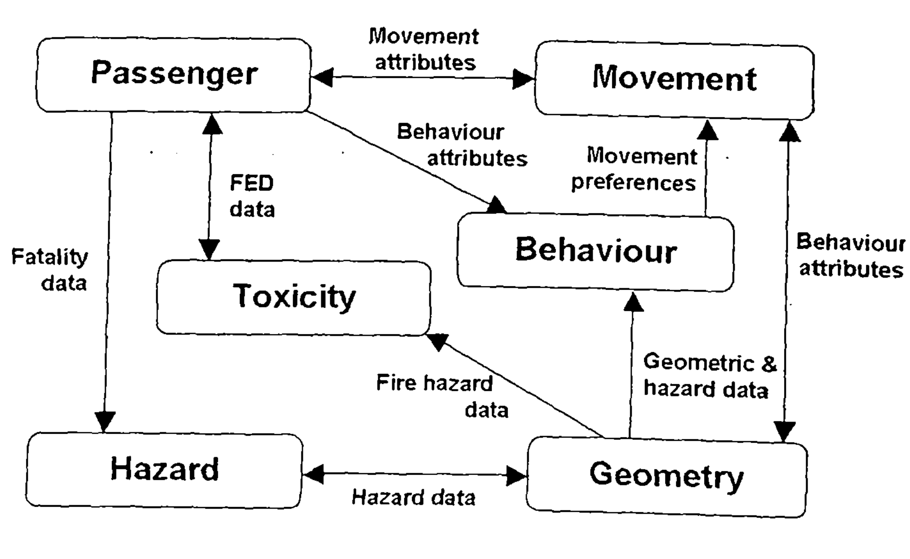

Figure 1. EXODUS submodel interacton

of space defined by the **GEOMETRY** of the enclosure. Each of these components will be briefly described in turn.

2.1.1 The GEOMETRY representation

The GEOMETRY of the enclosure can be defined manually or read from a Computer Aided Design using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0·5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space typically occupied by a single passenger.

2.1.2 The MOVEMENT submodel

The MOVEMENT SUBMODEL controls the physical movement of individual passengers from their current position to the most suitable neighbouring location, or supervises the waiting period if one does not exist. The movement may involve such behaviour as overtaking, side stepping, or other evasive actions.

2.1.3 The PASSENGER submodel

The PASSENGER SUBMODEL describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time, agility, etc. Each passenger can be defined as a unique individual with their own set of defining parameters. Cabin crewmembers require additional attributes such as, range of effectiveness of vocal commands, assertiveness at using voice commands, assertiveness when physically handling passengers and their visual access within certain regions of the cabin. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels. Passengers with disabilities may be represented by limiting these attributes.

2.1.4 The HAZARD submodel

The **HAZARD SUBMODEL** controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, radiation, smoke and toxic fire gases throughout the atmosphere and controls the opening and closing times of exits.

2.1.5 The TOXICITY submodel

The **TOXICITY SUBMODEL** determines the effects on an individual exposed to toxic products distributed by the hazard submodel. These effects are communicated to the behaviour submodel which, in turn, feeds through to the movement of the individual.

2.1.6 The BEHAVIOUR submodel

The **BEHAVIOUR SUBMODEL** determines an individual's response to the current prevailing situation on the basis of his or her personal attributes, and passes its decision on to the movement submodel. The behaviour submodel functions on two levels, global and local. The local behaviour determines an individual's response to the local situation e.g. jump over seats, wait in queue, etc while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, exit via the nearest serviceable exit, exit via most familiar exit or exit via their allocated exit. In the most recent research version of the software, cabin crewmembers can be identified and their behaviour specified to represent crew procedures. In this version, cabin crewmembers may perform specified duties during an evacuation such as opening exits, directing passenger flow, redirecting passengers to specific exits, continuous cabin flow monitoring with appropriate redirection, etc.

2.1.6.1 Passenger behaviour

While airEXODUS has the ability to represent 'extreme' passenger behaviour of the type reported in actual aviation accidents[23, 24], such as seat jumping, this type of behaviour is not included in these simulations. All the cases considered here are run under certification type evacuation conditions involving:

(i) Assertive cabin crew located at each Type-A exit,
(ii) Orderly passenger behaviour of the type found in certification evacuations,
(iii) Each exit being made ready in a representative time derived from past relevant certification tests.

As such, in the simulation of certification scenarios, the TOXICITY submodel is not utilised and only a limited range of the HAZARD submodel capability is utilised. All of the modelled scenarios that are presented within this paper were simulated under 90-second certification trial conditions and are thus representative of controlled physical experiments involving real passengers. Passenger performance and behaviour on stairs is based on data gathered from the marine and building environments (see section 3.1). This assumes that the staircase design is similar to that found in buildings.

2.1.6.2 Cabin crew behaviour

Previous research suggests that there is a relationship between the assertiveness of cabin crew members at exits and the achieved exit flow rates[6,7,25]. To reflect this passenger Exit Delay Time distributions have been determined to represent the varied levels of cabin crewmember assertiveness and their impact upon the flow rates through exits. The 'assertive' passenger Exit Delay Time distribution is used exclusively for this study.

A new feature of airEXODUS known as the Active Cabin Crew Management (ACCM) procedure is employed during some of the simulations described in this paper. While in the standard version of airEXODUS crew initiated actions were achieved implicitly through the setting of model parameters, using the ACCM system, the procedures are explicitly modelled. Thus the cabin crewmember is modelled as are their actions and the passengers response to those actions.

Cabin management procedures are usually employed by cabin crew during certification trials[26,27] and during real emergency evacuation situations[28-32]. These procedures may involve crew instigated exit by-pass or other passenger re-direction strategies. In applying these techniques the crew are attempting to either achieve a more efficient use of exits thereby reducing the overall evacuation time, or direct passengers away from a potentially dangerous cabin section. When attempting to reduce the overall evacuation time, crew are assessing the situation in their cabin zone and deciding when to redirect passengers onto another cabin zone or nearby exit.

In reality, the decisions made by the crew will be based on the information that they have on conditions around their exit and what they may know about other exits. The knowledge that the crew has of cabin conditions can be restricted due to line of sight, congestion, visibility in smoke, noise, etc. Alternatively, it may be enhanced by technical means such as conventional communication systems or novel new devices such as crew head-set communication systems, door visual display systems, etc. A feature of the ACCM procedures within airEXODUS is that the decision making capability of the crew can be restricted according to the prevailing conditions and the equipment at their disposal. The crewmember can also be given a radius of effectiveness. This dictates the region over which the commands made by the crewmember will be effective.

During certification evacuations, passengers are more compliant and are thus more likely to follow a crew command to redirect to another exit while in real situations this may be somewhat more difficult to achieve as passengers are more likely to be concerned with their own self interest. Both these situations can be represented within airEXODUS using the ACCM procedures. The first mode of operation is akin to 90-second certification trials in which passengers are generally compliant to all crew commands. The second mode attempts to model real emergency evacuations in which passengers are less compliant. In airEXODUS, when modelling certification evacuations, passengers are made to be compliant and thus follow all instructions issued by cabin crew.

In the simulations described in this paper, cabin crewmembers have been given complete information sets with respect to events within the aircraft cabin. As a consequence the procedures that are employed within these simulations should be considered as optimal or ideal.

2.2 Certification data used in airEXODUS

airEXODUS makes use of 90-second certification data[6] to specify certain model parameters[6]. In the work presented here, the most important parameter is the passenger Exit Delay Time. This time represents two stages of the exiting process, the exit hesitation time and the exit negotiation time. In virtually all cases, the passengers exhibit a hesitation at the exit, before negotiating it. Typically, this starts when an out-stretched hand first touches the exit. The latter time considers the amount of time taken to pass through the exit. Details concerning the exit hesitation time data used in airEXODUS may be found in[1, 6, 34].

For the purposes of this study, data corresponding to main deck Type-A exits with assertive cabin crew is used for the main deck. Data for upper deck exits of the type likely to be employed on VLTA is scarce. At present airEXODUS makes use of 90-second certification trial data from the upper deck of a B747[33].

Another key parameter in airEXODUS is the Exit Ready Time. This attribute represents the time required by a crewmember or passenger to render the exit escape system ready for use. The Exit Ready Time attribute was uniformly set at 14 seconds for every case considered within this report. Thus the total exit preparation time for each of the exits was set at 14 seconds. The exit preparation time used in this paper is considered conservative but not atypical of the exit preparation times required for Type-A exits.

3.0 EXAMPLE VLTA AND BWB EVACUATION MODEL APPLICATIONS

In this section we demonstrate three applications of the airEXODUS evacuation model to VLTA and BWB design. These will consider the use of staircases in double deck VLTA evacuation scenarios, the representation of cabin crew commands in VLTA evacuation and finally, the impact of BWB cabin layout on evacuation efficiency.

3.1 VLTA configuration issues examined using computer modelling

Here we demonstrate how evacuation models may be used to examine configuration issues associated with conventional VLTA. Several scenarios will be considered, namely the use of all exits on both decks, the use of half the normally available exits as in a certification demonstration trial and the use of all the exits on the main deck. The last case will require the upper deck passengers to make use of the main staircase during the evacuation.

3.1.1 VLTA test aircraft configuration

To demonstrate the use of airEXODUS a hypothetical VLTA was designed by the authors. The aircraft — designated the UOGXXX — has two decks and a capacity of 580 passengers in a three-class configuration. The upper deck seats 236 passengers in first and business class while the lower deck seats 344 passengers in first and economy class (see Fig. 2).

The UOGXXX has nine pairs of Type A exits, four on the upper deck and five on the lower deck. This is in excess of the six exit pairs that would be required to simply cater for the number of passengers[8]. The larger number of exits result from other regulations within FAR 25 that dictate that exits are required at each end of the cabin section and that the distance between any exit pair was not in excess of 60ft. Furthermore, the authors wished to avoid overwing upper deck exits. A schematic of the aircraft design is shown as Fig. 2.

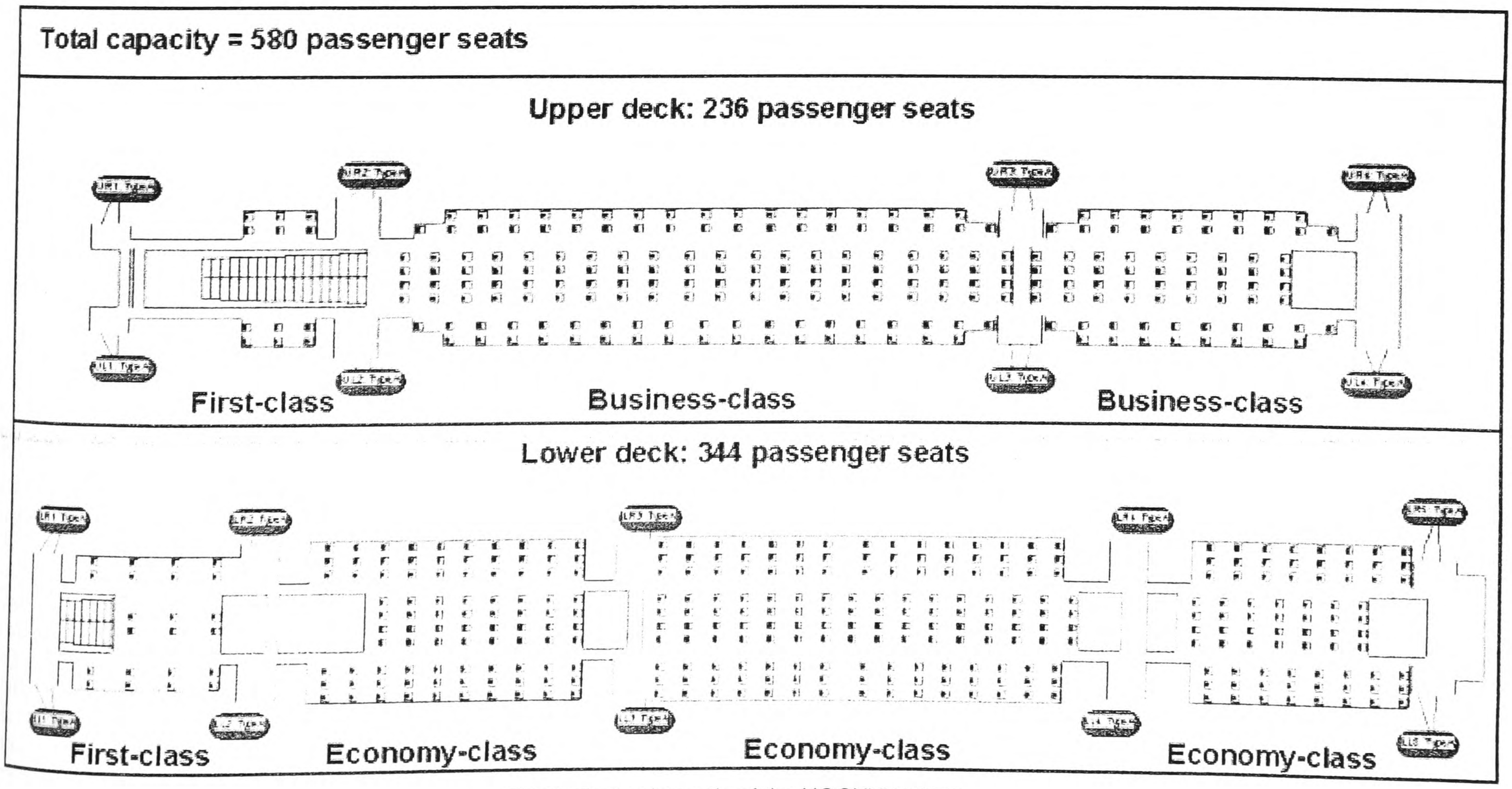

Figure 2. A schematic of the UOGXXX VLTA.

A staircase was positioned towards the front of the aircraft so as to assist in the expeditious boarding and disembarking of passengers. Other considerations included the desire not to split a class, maintaining a three class layout and causing minimal disruption to the first class passengers. The staircase was sufficiently wide to accommodate two passengers side by side separated by a central handrail. The staircase has dimensions typical of that found in buildings. Within airEXODUS, the behaviour of the passengers on the staircase is based on that found in buildings, where the speed of passengers is dependent on the age and gender of the passenger and whether they are travelling up or down the stair.

3.1.2 Population Specification

Passengers defined in airEXODUS are created using the 90-second Population function available in the software. This function generates the required numbers of passengers according to the specified mix (in terms of age and gender) as set out in FAR(35). In airEXODUS, simply specifying the age and gender of each passenger is not sufficient. Each person has 21 defining attributes, each of which must be assigned a value. The population tools in airEXODUS allow a range for each attribute to be specified, so that when a person is created, each attribute is assigned a random value between the limits set (see (1) for details).

3.1.3 Relevant airEXODUS parameters

Several airEXODUS parameters will be presented within this study. These are; Personal Elapsed Time (PET), Total Evacuation Time (TET), Cumulative Wait Time (CWT), Exit Flow Rates, Distance and OPS (see (1,12,19) for details).

The TET is a measure of the evacuation time for the aircraft. It is measured from the start of the evacuation to when the last passenger exits the aircraft. A single TET is determined for each evacuation simulation. Perhaps of more interest to an individual passenger is the PET. The PET is a measure of an individual's evacuation time. It is measured from the start of the evacuation to when the passenger has exited the aircraft. A PET is determined for each passenger in the evacuation simulation. The Response Time is the time a passenger takes to respond to the call to evacuate, release their seat restraint and stand. A Distance is calculated for each passenger. The Distance parameter records the total distance that each passenger had to travel during the evacuation.

The CWT measures the total amount of time a passenger has spent in congestion. This is measured after the passenger has completed their Response Time, i.e. unbuckled seat belts and stood up, to when the passenger has exited the aircraft. This can include time spent in the seat row attempting to get into the aisle, time spent stationary in the aisle and time spent queuing at the exit. A CWT is determined for each passenger in the evacuation simulation. In this paper, the PET and CWT that are quoted refer to the averages for all passengers for a particular run. This data is quoted as a range — numbers within the [] brackets — representing the minimum and maximum average for all the runs and as a single value. The single value represents the average of the average values.

The exit flow rate measure gives an indication of the performance of exits during an evacuation. It can be calculated for each exit by dividing the number of passengers that used the exit by the duration of the flow. An exit flow rate represents an average flow rate for the entire duration of passenger flow.

The OPS measure was designed by the authors to give an indication of the level of optimality of the evacuation with respect to balancing passengers to exit capacity(12,19). The OPS measure has been described in previous work and will not be described again here. Suffice to say that an OPS score of less than or equal to 0·1 is considered 'optimal' and OPS score in excess of 0·1 are considered non-optimal'.

The Off-Time (for Type-A exits) is the time required for the passenger to reach the ground once they have mounted the slide. Like the passenger Exit Delay Time, this is derived from certification data. However, in the present study, this is ignored. Thus the evacuation times represent the time out of the aircraft, not the on-ground times. If on-ground times are desired, a suitable slide time can be added to the TET.

3.1.4 Defining airEXODUS scenarios

All of the modelled scenarios that are presented within this paper were simulated under 90-second certification trial conditions and are thus representative of controlled physical experiments involving real passengers. Whilst airEXODUS has the capability of modelling more extreme behaviours of the type witnessed in real emergency evacuations they will not be activated in these scenarios. In addition, in all the cases examined the 'off-times' have not been included. To find the on-ground time it is necessary to add an appropriate slide time.

The scenarios considered in this section examine different combinations of exit availability and the impact that they have upon total evacuation time, exit flow rates and travel distances. In addition the type of cabin crewmember communication and procedures necessary to ensure an optimal evacuation are examined.

In total three main scenarios are considered. Scenario 1 investigates a precautionary evacuation in which all of the exits on the aircraft are available for use during the evacuation. This scenario provides an indication of the best possible evacuation time for the proposed aircraft design.

Scenario 2 investigates the standard 90-seconds scenario, in which only one side of the aircraft's exits are available for evacuation. This case provides an indication of how the UOGXXX will perform in a standard 90-second certification trial.

Scenario 3 represents a variation on the precautionary evacuation in which all passengers use the main deck exits. Thus passengers and crew from the upper deck are required to descend the staircase that joins the two decks. A variation of this scenario is also investigated in which cabin crew attempt to optimise the evacuation.

Finally, airEXODUS is stochastic in nature. This means that every time a simulation is repeated a slightly different evacuation time will result, as the individual passengers and crewmembers are unlikely to exactly repeat their actions. In addition, as the passenger Exit Delay Time is randomly attributed according to the specified distribution, passengers will not necessarily incur the same Exit Delay Time on exiting the aircraft in subsequent simulations. For this reason, it is necessary to repeat a simulation numerous times in order to generate a distribution of results. Each simulation case detailed in this paper has been run 1,000 times by airEXODUS to capture stochastic variations.

3.1.5 Scenario 1: Precautionary evacuation using all available exits

Scenario 1 simulated a precautionary evacuation in which all of the exits were available. These simulations generated an average total evacuation time of 46·8 [44·5–69·4] seconds, with an average personal evacuation time of 25·0 seconds (see Table 1). Furthermore, on average, a passenger wastes some 46% of their personal evacuation time in congestion. It is apparent that when all of the exits are available the UOGXXX can easily meet the 90-second evacuation requirement. This should come as no surprise, as the number of exits that are installed on the aircraft are well in excess of those required for the population size (see FAR 25(8)). The high OPS values indicate that the exit flows did not finish together. This suggests that it is possible to improve the evacuation times still further if a better passenger exit usage could be achieved. In particular the forward exits were under utilised. One way of achieving a better exit utilisation is to have a better passenger distribution between the exits. Another possible solution (at least for the certification case) would be to in-

Table 1
Summary of results for Scenario 1 (precautionary evacuation using all exits)

All Decks					Upper deck			Lower deck		
TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
46·8 [44·5-56·9]	11·6 [11·3-12·0]	7·2 [7·1-7·3]	25·0 [24·6-25·5]	0·23 [0·18-0·37]	44·6 [41·3-49·1]	236 [236]	0·24 [0·16-0·33]	46·7 [43·9-56·9]	344 [344]	0·22 [0·17-0·37]

troduce an active cabin management system that would allow cabin crew to by-pass passengers to the under utilised exits.

We also note that on average, the upper deck finishes 2·1 seconds ahead of the lower deck. It should be recalled that these times do not include the slide times. While not reported here in detail, it is also interesting to note that the generated exit flow rates of practically all the Type-A exits were below the average performance for Type-A exits under certification conditions[6]. The lower deck exits were 19% slower while the upper deck exits were 20% slower than expected. This lower than expected exit performance results from the relatively poor passenger supply to the exits which in turn is a result of having both exits in an exit pair operating.

In this scenario the achieved flow rates of the Type-A exits were constrained by the flow rates of the main and cross-aisles that supplied the exits. The cross-aisles were scarcely utilised in this scenario hence the supply of passengers to each exit was reduced. In the case of forward or aft exits and for some mid-section exits (depending on the nature of the cabin splits) passenger flow to the exit was limited as it was fed from a single main aisle (see Fig. 3(a)).

In contrast, in certification evacuation scenarios, only a single exit from an exit pair is available. In these cases both main aisles effectively feed the exit (see Fig. 3(b)), as passengers from the far main aisle make use of the cross aisle to access the exit.

In a balanced evacuation system, the supply of passengers to the exit should be broadly equivalent to the flow rate capability of the exits. In an ideal situation we should find that:

$$\text{Discharge (capacity)} \approx \text{Supply (capacity)} \qquad (1)$$

If an inequality exists between the supply or the discharge capacities either a bottleneck will develop (discharge < supply) or the exit will

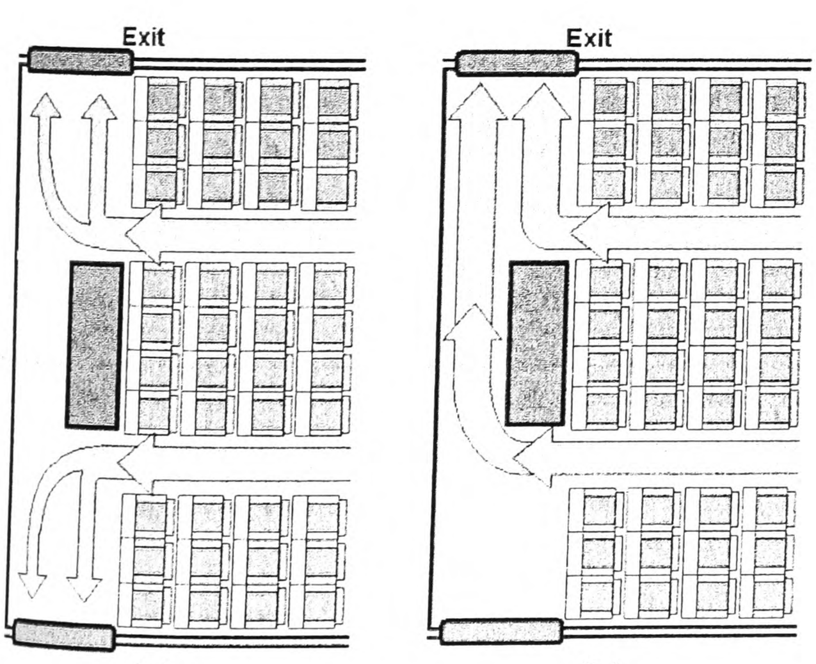

Figure 3. Hypothetical flow pattern at an end of section exit when (a) both exits from exit pairs are available and (b) one exit from and exit pair is available.

be under utilised (discharge > supply). In the case of Scenario 1, the supply capacity, i.e. the aisle, was less than the exit discharge capacity resulting in the poor exit flow rates achieved.

3.1.6 Scenario 2: Certification evacuation scenario

Scenario 2 investigated the evacuation of the UOGXXX under simulated 90-second certification trial conditions. Scenario 2 generated an average total evacuation time of 66·6 seconds and an average personal evacuation time of 34·3 seconds (see Table 2). Furthermore, on average, a passenger wastes some 57% of their personal evacuation time in congestion. As is to be expected, evacuation times have increased significantly relative to Scenario 1, but it is worth noting that the times have not doubled. These results, while ignoring the "slide times" suggest that the aircraft design could easily meet the requirements of the 90-second certification trial.

As with the previous case, the OPS for these simulations are quite large. This indicates that evacuation while achieving sub 90-seconds is inefficient. Overall evacuation times could be improved as suggested in the previous example.

Examination of the pattern of exit finishing times indicates that the forward exits finish some 33 seconds before the remaining exits. This resulted from the relatively low number of passengers located in the first-class cabin section. As such the forward exits were idle for much of the evacuation.

3.1.7 Scenario 3: Precautionary evacuation using lower deck exits

This scenario is similar to a precautionary evacuation in which only the lower deck exits are utilised. Here we are primarily interested in examining the performance of the staircase and its contribution to evacuation performance. In this scenario upper deck passengers are forced to descend the staircase to reach lower deck exits. In doing so, passengers have access to ten Type-A exits (i.e. more than half the normally available exits) all of which are located on the lower deck. The staircase connecting the two decks is positioned so that it empties onto the lower deck in the vicinity of the R1 and L1 exits.

When passengers are forced to use the internal staircase to access the exits on the lower deck, the evacuation time increases dramatically to an average of 149 [143·7-158·6] seconds (see Table 3). In this scenario while passengers have access to more than half the normally available exits, they are forced to travel a considerably longer distance (on average 13·9m (see Table 3) compared with 8·4m in Scenario 2 (see Table 2) to reach the exits and they must also traverse the staircase. The longer evacuation times may be due to the longer travel distances, the congestion on the stairs, the resulting access that the upper deck passengers have to the lower deck exits due to the location of the stairs, etc. Indeed, the longer evacuation times could be a function of all these factors. However, it should be noted that in an earlier publication the authors demonstrated that under certification conditions, simply travelling a longer distance does not necessarily incur a longer evacuation time[1].

In this scenario all the passengers coming down the staircase from the upper deck make use of the front two exits (R1 and L1). However, examination of the exit flow rates for the R1 and L1 exits on the

Table 2
Summary of the results of airEXODUS in Scenario 2 (certification evacuation scenario)

All Decks					Upper deck			Lower deck		
TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
66·6 [61·4-75·9]	19·5 [18·6-21·1]	8·4 [8·3-8·5]	34·3 [33·3-36·0]	0·25 [0·19-0·34]	64·1 [59·2-72·7]	236 [236]	0·22 [0·14-0·32]	66·1 [59·8-75·9]	344 [344]	0·32 [0·26-0·42]

lower deck reveal very poor flow rates were achieved. This suggests that the flow capacity of the exits was not the cause of the poor performance and that a bottleneck may exist somewhere else in the evacuation system.

Insight into the dynamics of this scenario was gained through examining the real time animation output from airEXODUS. Figure 4 depicts a frame from this animation at 48 seconds. This suggests that after 48 seconds the only passengers remaining on the aircraft are upper deck passengers. In addition, the graphics indicate that these passengers were forced to queue in the aisles of the upper deck whilst waiting to descend the staircase. Closer examination of Fig. 4 reveals that the cross-aisle area at the foot of the staircase was sparsely populated (the dashed circle in Fig. 4) in contrast to the densely populated reservoir at the top of the staircase (the solid circle in Fig. 4). Furthermore, Fig. 4 reveals that the staircase — represented by the vertical columns to the left of the diagram — were full of passengers. This leads to the conclusion that the staircase itself was contributing to the bottleneck, forcing passengers to queue on the upper deck.

Recall from Section 3.1.5 (Equation (1)) that in a balanced escape system the discharge capacity (the exits) must be broadly equivalent to the supply capacity (the aisles and cross-aisles). This concept can be extended to cover the larger evacuation system involving the staircase and upper deck. For Scenario 3, the notion of a balanced evacuation system can be extended to cover the supply from the upper deck, the stair connecting the decks and the final exits. This can be expressed as follows:

$$\text{Discharge (capacity)} \approx \text{Stair (capacity)} \approx \text{Supply (capacity)} \qquad (2)$$

The above analysis would suggest that the flow rate down the stairs is less than the supply rate from the aisles i.e. stair < supply, creating a bottleneck at the head of the stairs and that the discharge capacity of the stairs is less than the discharge capacity of the exits resulting in the under utilised exits i.e. discharge > stair.

From the study of video footage from past certification trials, the flow rate normally achieved through main cabin aisles is approximately 77·4 people/minute[6,34]. This average excludes people running at full speed down the aisle, but includes people fast walking. Under similar conditions, airEXODUS produces an average flow

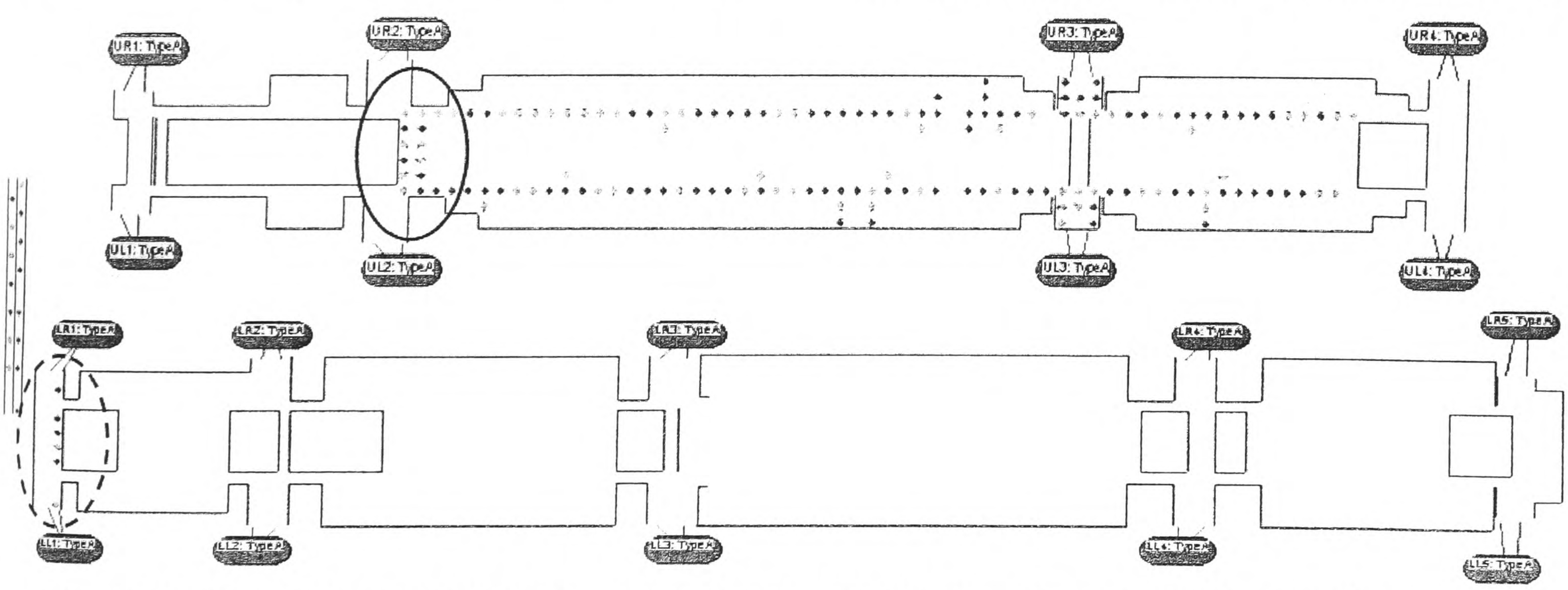

Figure 4. Graphic output from airEXODUS showing congestion at the top of the stairs 48 seconds after the start of the evacuation.

Table 3
Summary of results for Scenario 3 (use of lower deck only exits) and Scenario 4 (as Scenario 3 with active cabin crew management at the base of the staircase)

Scenario	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
	149·0 [143·7-158·6]	26·7 [25·7-27·8]	13·9 [13·7-14·1]	48·3 [47·1-49·4]	0·64 [0·62-0·66]	N/A	N/A	N/A	149 [143·7-158·6]	580 [580]	0·64 [0·62-0·66]
	148·5 [144·1-160·9]	26·9 [26·0-27·9]	13·9 [13·8-14·2]	48·6 [47·7-49·6]	0·58 [0·51-0·65]	N/A	N/A	N/A	148·5 [144·1-160·9]	580 [580]	0·58 [0·51-0·65]

rate of approximately 74 people/minute. The flow rate capacity for a standard stair as specified in the UK Building Code[39] is 80 people/minute/unit width. As with most data used in building codes this should be considered a conservative estimate. However, using this data, the staircase used in the UOGXXX would be conservatively rated according to the UK building code, with a capacity of approximately 80 people/minute. It should be noted that airEXODUS does not enforce a flow rate on stairs but specifies the behaviour and performance capabilities of passengers according to age, gender and direction of travel.

Clearly, as the staircase is fed by two aisles, each with an average flow rate capability of approximately 74 people/minute, the net flow rate into the stairs is potentially 148 people/minute, the stair capacity of approximately 80 people/minute will not be able to cope with this flow. This then results in a bottleneck developing at the head of the stairs, as shown by the airEXODUS simulations.

These results suggest that the situation may be improved either by introducing a wider staircase with three or more lanes or by including additional staircases. If wider staircases were considered, a point would be reached where the flow capacity of the staircase may exceed that of the two Type-A exits or that the flow capacity of the staircase would exceed that of the aisles feeding the stairs. To address these issues the staircase could be re-positioned, say to a location between two pairs of Type-A exits. Repositioning the staircase would potentially provide passengers with access to four Type-A exits and would also almost double the number of aisles feeding the staircase as passengers could be drawn from ahead of the stair as well as from behind the stair. All of these issues are being examined by the authors in further modelling research as part of a European Union (EU) funded research project under Framework V of the EU research plan. The project is known as VERRES.

3.2 Investigating VLTA cabin crew procedures using computer modelling

The airEXODUS software has the capability of simulating cabin crew procedures through the use of the Active Cabin Crew Management (ACCM) facility. This allows concepts in crew procedures to be tested on the computer before they are tried in full-scale simulators or in certification trials or in service. Here we examine if crew stationed at the base of the UOGXXX stairs can improve the stair performance thereby decreasing evacuation times found in Scenario 3 and if crew implemented by-pass procedures can improve the outcome of the certification scenario simulation.

4.2.1 *Scenario 4: Crew procedures addressing staircase performance*

Two cabin crew were assigned duty stations on the lower deck (see Fig. 5) by the bottom of the stairs. Each was given the task of optimising the evacuation via redirecting passengers to adjacent exits when they deemed it appropriate. This meant that the crewmember on the left of the aircraft could assign passengers to use doors L1 and L2, while the crewmember on the right of the aircraft could assign passengers to doors R1 and R2.

As part of the ACCM system[38], crewmembers need to access and process a considerable amount of information. When controlling the flow between two exits, the crewmember needs to know, the number of passengers using each of their assigned doors at any time i.e. the congestion levels at the doors, the number of passengers that may require to use the door i.e. the number of passengers in the catchment area of the door, how each of their assigned doors is performing i.e. the achieved flow rate and the time it would require passengers to move between the doors. Crewmembers also have a radius of effectiveness in which they can exert an influence on the passengers i.e. effectively touch distance and voice control distance. The act of communicating with passengers also requires a certain amount of time during which other passengers may be able to get by without

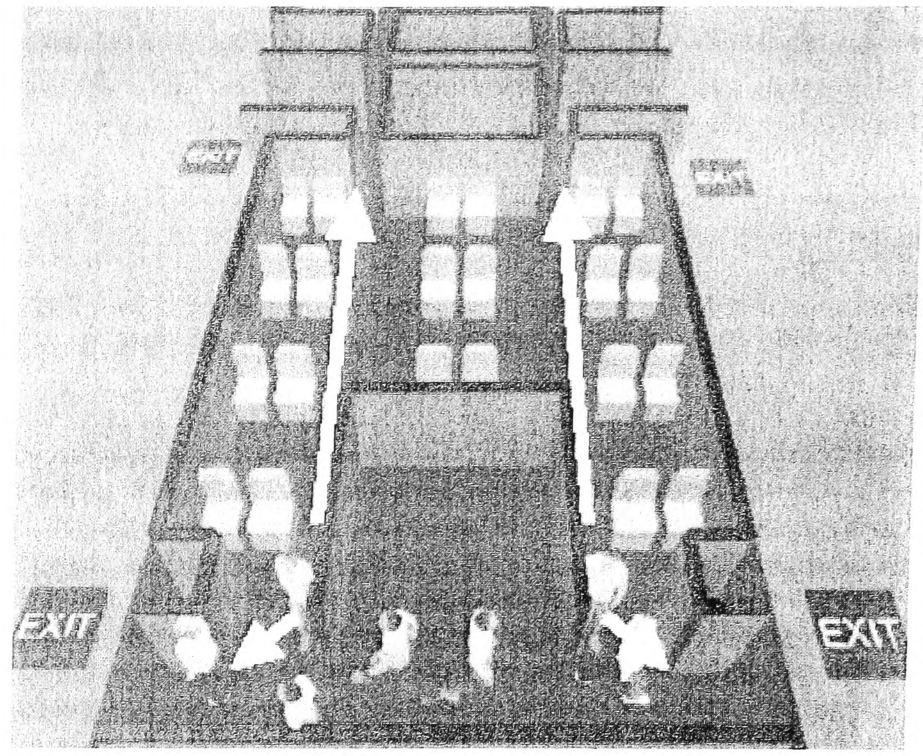

Figure 5. The cabin crewmember redirection stations and exit responsibilities (denoted by arrows) on the lower deck.

being influenced by the crewmember. Furthermore, passengers are given a compliance factor which determines how likely they are to follow the crewmembers instructions[38].

In the examples discussed here, the crew are considered to have complete knowledge of all the factors required to make perfect re-direction decisions. Furthermore, the passengers are considered to be compliant (see Section 2.1.6.2). In this example — Scenario 4 — the crew will attempt to redirect passengers from the L1 and R1 exits only if they determine it will result in an overall net benefit to the evacuation time of the aircraft. Thus, this scenario should be considered to be an ideal case.

The results for this scenario are presented in Table 3. As can be seen, the crew procedures at the bottom of the staircase did not improve the evacuation time of the aircraft. Results from the simulations indicate that only a very small number of passengers were redirected. In this case the crew determined that there would be no net benefit from redirecting the passengers to the other exit. What redirection has occurred has had virtually no impact on the average evacuation times however, the OPS has improved marginally (indicating a better usage of the exits) while the average personal evacuation time has increased marginally. This supports the conjecture raised in Section 3.1.7 that it is not the capacity of the exits that is at fault in this case but the staircase design and location are the likely causes of the poor performance.

To demonstrate the flexibility of the ACCM procedures, the crew at the base of the stairs were given an alternative redirection procedure. In the modified case — Scenario 4b — the crew were instructed to redirect every other passenger descending the stairs to the number 2 exits. Using this procedure we note that the average distance travelled increases as the redirected passengers are forced to travel slightly further to exit the aircraft. More significantly, the average total evacuation time increases from 148·5 seconds to 160·6 seconds (see Table 4). These results further support the point made earlier that the flow capacity of the exit is not the cause of the long evacuation times and crew procedures at the base of the stairs cannot assist in reducing the overall evacuation times.

3.2.2 *Scenario 5: Improving VLTA performance during certification trials through cabin crew procedures*

As was shown in Scenario 2, the UOGXXX was able to comfortably

Table 4
Summary of results for Scenario 4 (as Scenario 3 with Active Cabin Crew Management at the base of the staircase) and Scenario 4b (crew instructed to redirect every other passenger descending the stairs)

	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
4	148·5 [144·1-160·9]	26·9 [26·0-27·9]	13·9 [13·8-14·2]	48·6 [47·7-49·6]	0·58 [0·51-0·65]	N/A	N/A	N/A	148·5 [144·1-160·9]	580 [580]	0·58 [0·51-0·65]
4b	160·6 [150·5-172·5]	27·1 [26·2-28·1]	14·8 [14·7-15]	49·6 [48·7-50·7]	0·52 [0·5-0·56]	N/A	N/A	N/A	160·6 [150·5-172·5]	580 [580]	0·52 [0·5-0·56]

complete an evacuation under certification conditions within 90-seconds. However, the OPS under these conditions was quite large indicating that evacuation, while achieving sub 90-seconds, was inefficient. Examination of the results suggest that the forward exits on both decks finish considerably earlier than the other exits. This is a result of the low density first class cabin sections located at the front of the aircraft on both decks.

A possible means of improving this situation would be to have the crew at the deactivated number 2 doors (on both decks) re-direct passengers forward to the number 1 door when appropriate (see Fig. 6). This function would be performed in addition to their task of protecting the deactivated door. Thus passengers in the left aisle would occasionally be redirected forward to the R1 door.

In this case (Scenario 5), as in Scenario 4, the crew are given perfect and complete knowledge and the passengers are compliant. The effective radius of operation of the crew is set to 2m.

The results for this scenario are displayed in Table 5. As can be seen, the introduction of ACCM has succeeded in reducing the overall evacuation time and significantly reduced the OPS to a near optimal average state (i.e. OPS < 0.1). Approximately 20 passengers on average were redirected on the upper and lower deck. As is to be expected, the average distance travelled by the passengers has increased slightly. This is due to the extra distance travelled by some passengers during the by-pass process.

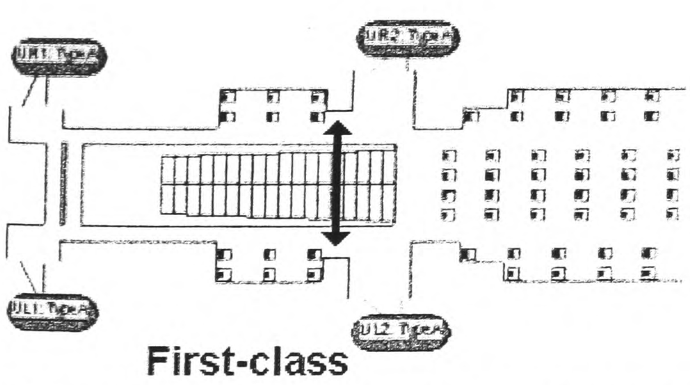

Figure 6. The cabin crewmember redirection station (denoted by arrows) on the upper deck, a similar station exists on the lower deck.

3.3 BWB seating configuration Issues examined using computer modelling

Here we demonstrate how evacuation models may be used to examine configuration issues associated with un-conventional BWB aircraft design. Several scenarios are considered involving different aisle and seating configurations. The nature of the BWB design makes it difficult or impossible for the conventional FAR regulations to apply. The BWB design concept prohibits exits on the side of the aircraft and so all 'conventional' exits will be restricted to the forward central leading edge or the rear of the aircraft. In the example considered here, FAR rules relating to cabin layout are adhered to wherever possible.

3.3.1 BWB Test section configuration and Scenarios

In the demonstration analysis described here only a section of the BWB aircraft is considered. Three alternative designs are considered corresponding to the rear end of the aircraft. The first section modelled consists of 420 passengers located in five rows seated 3,5,5,5,3 abreast (Scenario 6). This section consists of four inner main passenger aisles. The second section (Scenario 7) consists of the same number of passengers and seating configuration however two additional outer aisles are provided. The final case (Scenario 8) consists of 500 passengers located in five rows seated 5,5,5,5,5 abreast. This section consists of four inner aisles and two outer aisles (see Fig. 7). In all cases, passengers are seated no more than three seats away from an aisle.

The seat pitch in each case is identical (30in) as are the aisle widths (20 inches). At the rear of each cabin section is a large unobstructed cross aisle 2m deep. Also located at the rear of the cabin section are four Type-A exits. The model makes use of the standard exit hesitation time distribution for assertive cabin crew and Type-A exits. As the section examined only represents a portion of the aircraft geometry, it is implicitly assumed that the aircraft has addition-

Table 5
Summary of results for Scenario 2 (certification scenario) and Scenario 5 (as Scenario 2 with active cabin crew management at door 2 on both decks)

nario	All Decks					Upper deck			Lower deck		
	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS	TET (secs)	Evacuees (pax)	OPS	TET (secs)	Evacuees (pax)	OPS
	66·6 [61·4-75·9]	19·5 [18·6-21·1]	8·4 [8·3-8·5]	34·3 [33·3-36·0]	0·25 [0·19-0·34]	64·1 [59·2-72·7]	236 [236]	0·22 [0·14-0·32]	66·1 [59·8-75·9]	344 [344]	0·32 [0·26-0·42]
	59·1 [55-64·8]	17·2 [16·3-18·1]	9·2 [9·1-9·3]	32·7 [31·9-33·6]	0·1 [0·04-0·19]	58·6 [54·7-64]	236 [236]	0·09 [0·02-0·18]	57·4 [52·6-64·8]	344 [344]	0·11 [0·03-0·24]

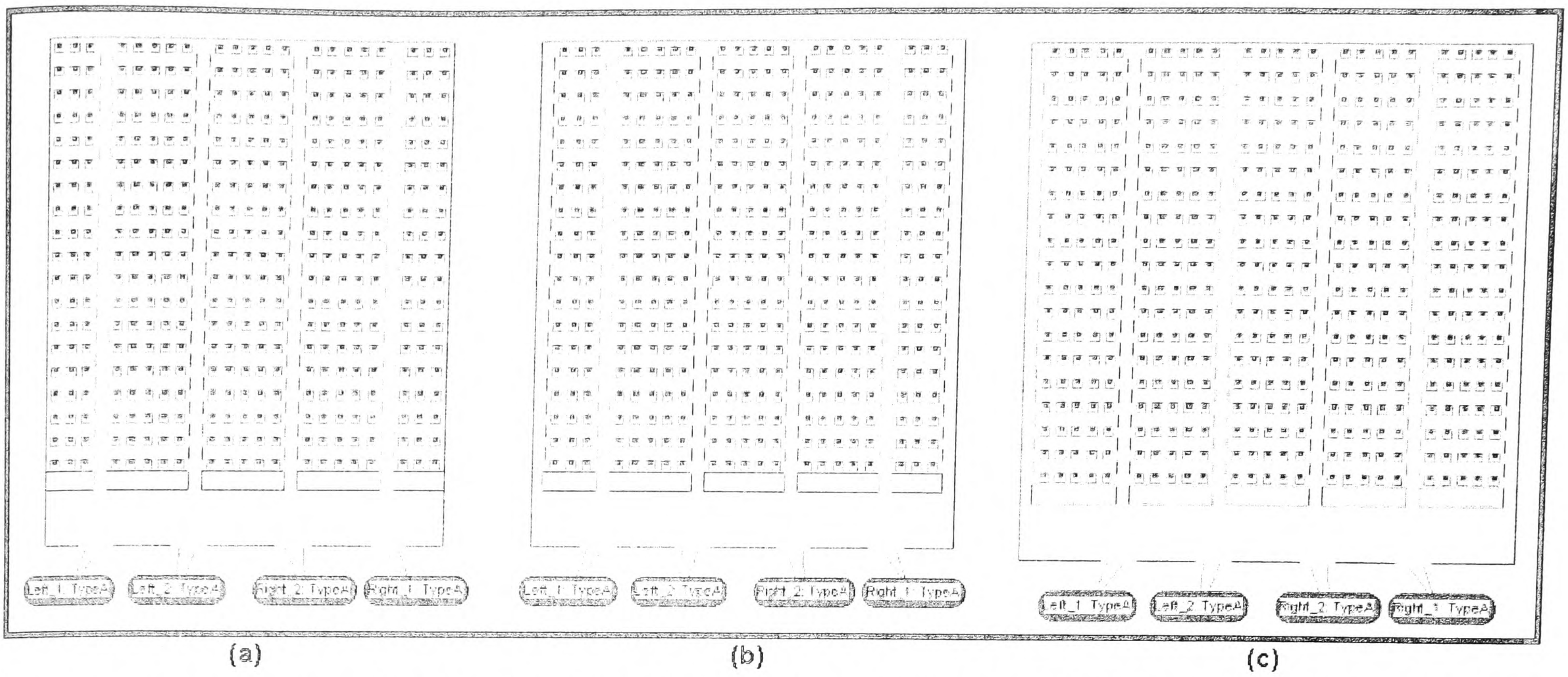

Figure 7. Three different BWB test sections represented within airEXODUS. The three sections consist of (a) a seating configuration of 3-5-5-5-3 with 420 passengers (Scenario 6), (b) a seating configuration of 3-5-5-5-3 with perimeter aisles also seating 420 passengers (Scenario 7) and (c) a seating configuration of 5-5-5-5-5 with perimeter aisles seating 500 passengers (Scenario 8).

al seating capacity and additional exits towards the forward of the aircraft. The passenger populations are specified as described in Section 3.1.2 and all exits are assumed to be opened and ready for use after 11·1 seconds.

3.3.2 Scenarios 6,7 and 8: BWB evacuation performance

In a conventional aircraft, the passenger load represented by Scenarios 6 and 7 would easily be accommodated in an aircraft with four pairs of Type-A exits. In such a conventional aircraft four exits would be used for the certification trial and the aircraft would be expected to produce a sub 90-second certification evacuation performance.

In Scenario 6 we find that the average total evacuation time is in excess of 90-seconds (see Table 6). The results suggest that while the exits are reasonably well balanced (OPS < 0·1), the exit flow rates are sub-optimal. In effect, the exits are being under utilised. The four main cabin aisles cannot supply sufficient passengers to keep the four Type-A exits working at full-capacity. Using the notation of Equation (1) we have discharge > supply. It is also interesting to note from the airEXODUS real time animation output that the cross aisle at the rear of the aircraft never appears fully congested.

In an attempt to improve the passenger flow to the exits two additional aisles were added to the aircraft (Scenario 7) and the simulation repeated. In this situation the total evacuation time greatly decreases to an average of 73·4 seconds, thus satisfying the 90-seconds requirement. In this case the cumulative wait time (CWT) associated with congestion has also significantly decreased (see Table 6). Furthermore, the exit flow rates for each exit have increased and are close to their maximum practical average values[6,34].

As the evacuation time has decreased significantly through the introduction of the outer aisles, it may also be possible to increase the passenger load that can be serviced by the existing exits. In the final case (Scenario 8) the passenger load is increased to 500 through the addition of four additional seats to each row, two on the left and two on the right. In this case the average total evacuation time has increased to 81·8 seconds, still satisfying the 90-second requirement. It is interesting to note that in this case the average CWT has increased compared with the previous case reflecting the increased congestion experienced throughout the aircraft.

One area that requires further research is the behaviour of passengers in passing through the large open cross aisle space at the end of the aircraft. In the model, the passengers are assumed to break into their fast walk speed. Because of the more open space they are not hindered by slower moving passengers and can overtake. However, would passengers break into a faster running mode when they entered such a region?

This brief analysis suggests the supply of passengers to closely located exits will be a critical factor in determining the evacuation efficiency of exits. Simply increasing the number of exits or making the exits wider will not improve the evacuation performance of the BWB aircraft. However, improving the supply of passengers to the exits either by adding additional aisles — as demonstrated here — or perhaps by making the aisles wider could serve to improve overall evacuation capability.

4.0 CONCLUSIONS

This paper has demonstrated how aircraft evacuation models can be

Table 6
Overall airEXODUS statistics for the three BWB cabin layouts

Scenario	Overall statistics					
	Pax	TET (secs)	CWT (secs)	Dist (m)	PET (secs)	OPS
6	420	92[85·5-99·9]	27·8[26·4-29·2]	11·3[11·2-11·5]	45.3[43·7-46·6]	0·09[0·02-0·17]
7	420	73·4[68·9-80·7]	18·5[17·4-20]	12·6[12·2-12·9]	37.6[36·2-39·4]	0·08[0·01-0·18]
8	500	81·8[77·4-88·1]	22·5[21·3-24·2]	13·4[13-13·7]	42.5[41·1-44·4]	0·08[0·01-0·17]

used to address a range of issues associated with the design of conventional VLTA and the more unusual cabin layouts associated with BWB aircraft cabin design.

When considering the evacuation efficiency of aircraft design, much can be learned about the potential performance of the aircraft layout by considering the aircraft as an escape system made up of a series of sub-components. These sub-components have a supply and discharge capability that must be balanced in order to achieve an efficient evacuation performance. Using this concept and the results from a dete ed modelling exercise, it was shown that staircase design and location are critical factors in evacuation scenarios where passengers are required to use the lower deck exits on a double deck aircraft. In the specific design investigated, it was shown that the two-lane staircase could not cope with the passenger flow generated by the two main cabin aisles resulting in a bottleneck at the head of the stairs and under-utilisation of the main deck exits. Suggestions for improving the overall evacuation time under such conditions include, widening the staircase or providing an additional staircase. If the staircase was widened, it may also prove necessary to move the staircase to an alternate location.

It was also shown how crew procedures could be represented in aircraft evacuation models and how this could be used to assist in the development of crew procedures, and for exploring the potential usefulness of devices such as communication head sets for relaying information that would otherwise not be available to the crew.

In examining BWB cabin concepts it was clear that the supply of passengers to closely located exits will be a critical factor in determining the evacuation efficiency of the exits. Simply increasing the number of exits or making the exits wider will not necessarily improve the evacuation performance of the BWB aircraft. However, improving the supply of passengers to the exits either by adding additional aisles — as demonstrated here — or perhaps by making the aisles wider could serve to improve overall evacuation capability.

An important issue that must be borne in mind is that gaps exist in our understanding of human behaviour and performance in some of the configurations examined. One of the areas that requires further attention is the collection of passenger exit hesitation time data at high sill height exits. While some data exists, more data is required to increase the confidence in model predictions. However, where data does not exist in abundance, models can also be used to limit and refine the design concepts that may need testing in experimental facilities. Clearly, a sensible balance of modelling and experimentation is required to address all of the challenging issues posed by VLTA and BWB aircraft.

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